Forest Research Report **152**

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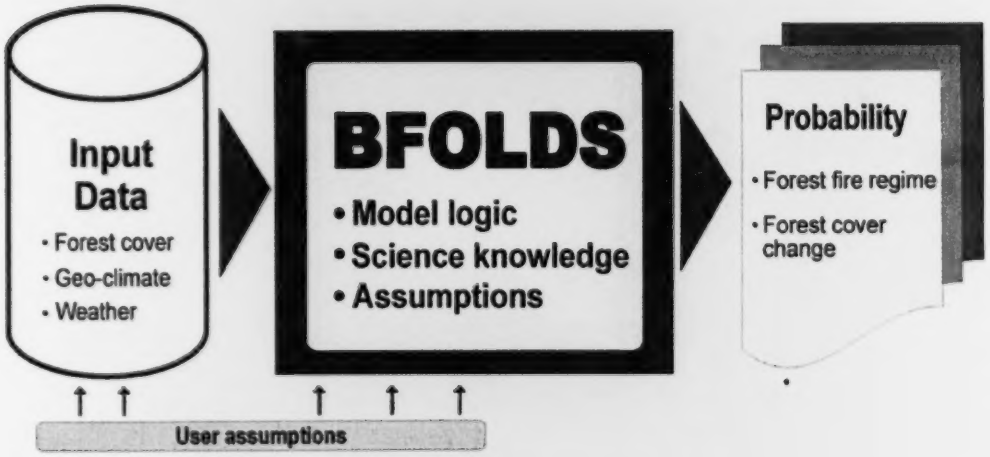
A spatial simulation model for exploring large scale fire regimes and succession in boreal forest landscapes



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A spatial simulation model for exploring large scale fire regimes and succession in boreal forest landscapes

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Abstract

Boreal forest landscape dynamics simulator (BFOLDS) is a fire regime-succession simulation model that can be used to explore long-term forest cover changes at large spatial extents. This report documents BFOLDS' structure, components, assumptions, functionality, and applications. An appended user manual provides instructions for using BFOLDS 1.0, the graphics user interface-based software package that contains the simulation model.

BFOLDS abstracts forest fire and succession processes quantitatively and stochastically in a spatially explicit manner. It logically combines fire ignition, growth, and extinguishment with forest succession based on input data of weather, forest composition, terrain, and soil. Simulation of these processes is accomplished by two interacting components: a fire simulation module and a forest succession module. The fire simulation module is process-based and primarily founded on published fire science knowledge of Canadian Forest Fire Behaviour Prediction System and Fire Weather Index system and consists of sub-modules for ignition, spread, and extinguishment of simulated fire events. The forest succession module is empirically based, and driven by a time-dependent Markov model, populated by user-input rules on forest cover transitions specific to a hierarchy of site conditions. BFOLDS is a raster-based model, operating at 1 hectare spatial resolution. Its temporal resolution varies from a day to a year, depending on the simulated process.

BFOLDS is designed to discover characteristics of large scale boreal fire regimes, as emerging properties of synthesized knowledge and assumptions of weather, fire behaviour, forest fuel, and forest succession. Thus model users have opportunities to examine effects of their assumptions and input data on characteristics of simulated fire regime. These simulated scenarios of forest landscape dynamics are not meant to reflect the past, present, or future, but are a set of hypotheses extended based on model logic, assumptions, and input. We recommend BFOLDS for use in exploring the spatio-temporal variability in boreal forest fire regime based on what-if scenarios and assumptions as a research tool and to inform strategic applications of designing forest land use plans and developing forest policy.

Resumé

Le simulateur de la dynamique des paysages de la forêt boréale (BFOLDS) est un modèle de simulation de la succession du régime d'inflammabilité qui peut servir à examiner l'évolution à long terme du couvert forestier sur de grands espaces occupés. Le présent rapport documente la structure, les composantes, les hypothèses, la fonctionnalité et les applications du modèle. Un guide de l'utilisateur en annexe fournit des directives sur l'utilisation du modèle BFOLDS 1.0, le progiciel basé sur une interface utilisateur graphique qui contient le modèle de simulation.

Le modèle BFOLDS résume quantitativement et stochastiquement les processus d'incendie de forêt et de succession de manière spatialement explicite. Il combine logiquement l'allumage, le développement et l'extinction d'incendies avec la succession des forêts basée sur les données d'entrée relatives au temps, à la composition de la forêt, au terrain, et au sol. La simulation de ces processus est effectuée par deux composantes interdépendantes : un module de simulation d'incendie et un module de succession de forêt. Le module de simulation d'incendie est basé sur un processus et fondé principalement sur les connaissances publiées relatives à la science du feu de la méthode canadienne de PCI et de l'IFM et est constitué de sous-modules relatifs à l'allumage, à la propagation, et à l'extinction d'incendies simulés. Le module de succession de forêt est basé sur une méthode empirique, et dicté par un modèle markovien dépendant du temps qui comporte les règles d'entrée utilisateur relatives aux transitions du couvert forestier propres à une hiérarchie de conditions du site. BFOLDS est un modèle basé sur une trame, qui fonctionne à une résolution spatiale de 1 hectare. Sa résolution dans le temps varie d'une journée à une année, selon le processus simulé.

Le modèle BFOLDS est conçu pour découvrir les caractéristiques des régimes d'inflammabilité boréaux à grande échelle, comme les nouvelles propriétés des connaissances et des hypothèses synthétisées relatives au temps, au comportement des incendies, aux combustibles forestiers, et à la succession des forêts. En plus de la saisie des données, les utilisateurs du modèle ont des occasions d'examiner la réponse des régimes d'inflammabilité à leurs hypothèses. Nous recommandons l'utilisation du modèle BFOLDS dans l'examen de la variabilité spatio-temporelle dans le régime d'inflammabilité des forêts boréales fondé sur des scénarios hypothétiques et des hypothèses comme outils de recherche et recommandons de fournir des renseignements sur les applications stratégiques de la conception de plans d'aménagement des terres forestières et de l'élaboration d'une politique forestière.

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Introduction

Goal

BFOLDS is an acronym for the PC-based computer simulation model *Boreal Forest Landscape Dynamics Simulator*. Boreal forest landscapes consist of spatially and temporally shifting mosaics of forest cover, driven primarily by frequent and intense forest fires. Therefore, how well we gain insights into the ecology of boreal forest landscapes depends largely on how well we understand the nature of fire regimes – the long-term spatial and temporal variability in forest fire occurrences in large expanses of land – and subsequent forest succession.

The primary intent of this report is to provide readers with an understanding of BFOLDS with respect to its principles, structure, and applications. Accordingly, we have organized the report to answer the questions: *What is BFOLDS?, How does BFOLDS work?,* and *What are appropriate uses of BFOLDS?* A basic understanding of boreal forest landscapes, forest fire regimes, forest succession, and simulation modelling are essential to use BFOLDS.

While we may elucidate aspects of some of these fundamentals, the responsibility and ability to provide comprehensive details of that knowledge is beyond the scope of this document. Therefore, we assume that the reader has that understanding – if not, we strongly recommend that the reader acquires the prerequisite knowledge before attempting to use BFOLDS.

A basic understanding of boreal forest landscapes, forest fire regimes, forest succession, and simulation modelling is an essential requirement for using BFOLDS. While we may elucidate some aspects of these fundamentals, the responsibility and ability to provide comprehensive details of that knowledge is beyond the scope of this document. Therefore, we assume the reader has that understanding – if not, we strongly recommend that the reader acquires the prerequisite knowledge before attempting to use BFOLDS.

A supplementary document, which is appended to the main report, provides detailed instructions for *how to access and use* the software package that contains BFOLDS. As well, a forthcoming document will present a case study example of applying BFOLDS to simulate fire regime in a boreal forest landscape.

Background

Boreal forest landscapes consist of spatially and temporally shifting mosaics of forest cover, driven primarily by frequent and intense forest fires. Therefore, how well we gain insights to the ecology of boreal forest landscapes depends largely on how well we understand the nature of fire regimes – the long-term spatial and temporal variability in forest fire occurrences in large expanses of land – and subsequent forest succession.

Knowledge of forest landscape dynamics caused by fire disturbance regimes is long recognized as a prerequisite to managing boreal forests, where fire regimes are considered as a null model and a benchmark for designing forest management practices at broad spatial and temporal scales (Perera and Buse 2004). While numerous methods are available to understand natural fire regimes and ensuing forest landscape dynamics, all of them belong to two broad groups of approaches (Suffling and Perera 2004).

The first, and more traditional group, is the *historical (observational) techniques* where empirical evidence of past forest fires and forest cover changes is collected and used, deductively, in re-constructing the forest landscape dynamics. These specific techniques range from examining historical documents such as survey records to investigations of tree rings or buried charcoal and pollen to collect evidence of historic forest fires and species composition. For further details on such dendrochronological and paleoecological investigations, we refer the reader to the comprehensive review by Egan and Howell (2001). Regardless of the differences in techniques, all historical observational methods describe a single or few fire events and subsequent forest land cover changes, which limit their inference base to one or few scenarios of many possibilities.

The second group of methods is relatively new and includes *scenario simulation techniques* where scientific knowledge of the processes in forest fire and forest cover changes, sometimes in combination with empirical evidence, are abstracted as quantitative expressions of forest landscape dynamics. As Suffling and Perera (2004) indicated in their review, these methods fall broadly into statistical or mechanistic categories, primarily based on their approaches of extracting model functions, or sometimes a combination of the two (hybrid category). Moreover, as Keane et al. (2004) point out, simulation model methods are proliferating rapidly and a range of sub-categories are emerging based on the specific differences in modelling techniques. In general, most scenario simulation modelling methods are aimed at describing multiple fire events and their consequences, while examining the variability and stochasticity associated with fire-forest landscape dynamics. Although this document focuses on a simulation model, a comprehensive review and discussion of fire-landscape dynamics modelling techniques is beyond its scope. Instead, the reader is referred to extensive reviews of fire modelling approaches at landscape scale in literature, for example Gardner et al. (1999) and Keane et al. (2004).

The premise of the approaches to understanding fire regimes and forest landscape dynamics can be illustrated as a Venn diagram (Figure 1). For a given forest landscape, the *potential* landscape dynamics (depicted by the large circle in Figure 1) represent the full range of all possible landscape dynamics (i.e., fire regimes and forest cover changes); *past* landscape dynamics represent the historic fire events and forest cover changes; and *future* landscape dynamics represent those changes expected to occur within a specified future timeframe. This figure conveys several simple messages:

(a) historical landscape dynamics are a small subset of the potential landscape dynamics,

(b) future landscape dynamics are also a small subset of the potential landscape dynamics,

(c) the historical and future landscape dynamics may overlap, perhaps just by chance, and that overlap explains the landscape dynamics common to the past and future, and most importantly

(d) different study methods address different specific views of landscape dynamics.

While we will refer to and discuss Figure 1 further in later sections, its present relevance is that BFOLDS is a method to explore the *potential* forest fire regime and ensuing forest cover changes.

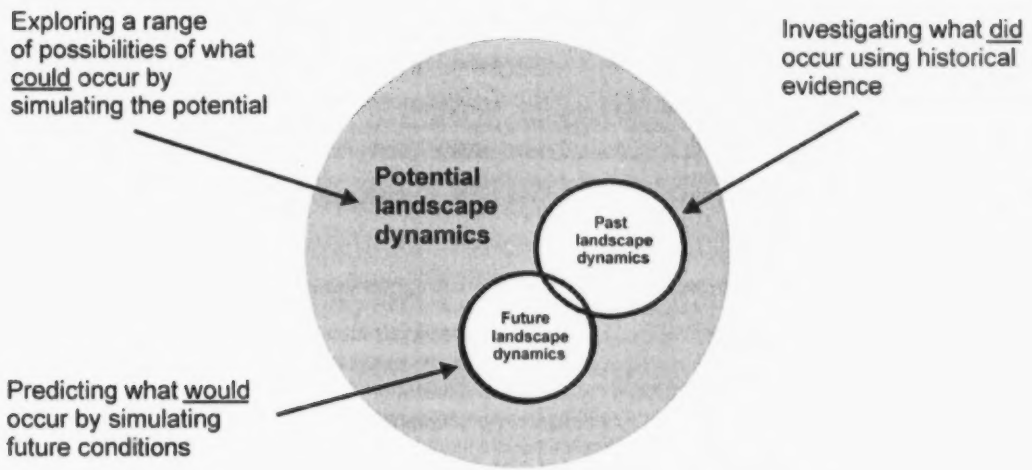
Exploring a range of possibilities of what could occur by simulating the potential
Investigating what did occur using historical evidence
Potential landscape dynamics
Past landscape dynamics
Future landscape dynamics
Predicting what would occur by simulating future conditions

Figure 1. *A logical expression of past, future, and potential landscape dynamics and means of understanding those domains.*

What is BFOLDS?

The acronym BFOLDS contains a numerical suffix to indicate its vintage because the model is designed to accommodate incremental improvements in science, knowledge, and information. This public domain version of BFOLDS is designated 1.0, and is the result of many cycles of testing, calibrations, and improvements of a series of prior prototypes (Perera et al. 2003, Weaver and Perera 2004, Perera et al. 2004, Cui and Perera 2008, Cui et al. 2008, Perera et al. 2008). BFOLDS 1.0 is packaged in a graphics user interface and contains several peripheral tools to facilitate its use. In future, we plan to release improved versions of BFOLDS, and the significance of those changes will be denoted by changes in the numerical suffix.

BFOLDS is designed to explore possibilities of forest fire regime (for example, fire return interval, fire sizes, and spatial patterns in burns), forest succession (for example, transition trajectories, forest cover residence probabilities), and their interactions (for example, forest cover aging) in boreal forest biomes – all require investigations at large spatial extents (millions of hectares) and over long time periods (centuries).

In essence, BFOLDS quantitatively abstracts the processes (in this case boreal landscape dynamics) based on a logical combination of known mechanisms (for example, forest fire ignition, spread, and extinguishment), present state-of-knowledge (for example, expected forest succession trajectories), and extant data (for example, forest cover composition, terrain, and soil). Those parts of the model that contain simulations of forest landscape processes (for example, forest fire spread) based on the most recent published science are *mechanistic* or *process-based*, and generate results that emerge (for example, fire sizes and shapes) but are not known or assumed *a priori*. Other parts of the model contain simulations of the outcomes of forest landscape processes (for example, forest succession) based on best available knowledge and/or science. These modelling steps are *empirical* and generate results (for example, forest cover transition) within known and/or assumed ranges of possibilities. Given its combination of both mechanistic and empirical modelling logic, we categorize BFOLDS 1.0 as a hybrid model (*sensu* Keane et al. 1996).

Several other characteristics of BFOLDS, although described in detail in subsequent sections, must be mentioned here. Model input, logic, and output are dealt with in a grid-based computational environment, where the spatial scale is fixed at 1 ha pixel size. BFOLDS simulations are also spatially explicit because all data layers and computations are geo-referenced and consider spatial biases and neighbourhood interactions whenever feasible (for example, fire spread, forest cover change). The temporal resolution of BFOLDS varies with specific model functions (for example, minutes for fire spread and years to decades for forest cover changes). However, the most noteworthy feature of BFOLDS is the degree of stochasticity embedded in its logic of simulating forest fires and forest succession. As a result, repeated model simulations with the same input data result in different fire regimes and different forest succession patterns as an emergent property, and capture the variability that exists in natural dynamics in forest landscapes.

Because the state of knowledge, information, and data will always be imperfect and incomplete, as with all simulation models, BFOLDS also contains many assumptions in its abstraction. As a result, modelled forest landscape dynamics are assumption-bound and these scenarios are considered as *simulations of what could occur* strictly and only within the context of those assumptions.

Since all assumptions, logic, knowledge, information, and data within the BFOLDS model structure are quantitative and explicit, users can explore different possibilities of forest landscape dynamics that result from a range of assumptions and data input. BFOLDS therefore can be viewed as an objective tool that informs about large scale forest fire processes and forest succession in the boreal forest biome, based on an explicit synthesis of the present states of science, knowledge, information, data, and assumptions.

Furthermore, it realizes *probabilities* of such forest landscape dynamics that arise from innate *variability* in nature. BFOLDS does so by replicating simulations many times using the same basic information for a given

BFOLDS is not meant to be used as a tool to produce deterministic information (for example for drawing a map of forest cover composition in a given year) or used to investigate fine-scale processes (for example the behaviour of individual forest fire events or single-stand forest composition changes).

forest landscape, and separating this variability into three dimensions: spatial (variability from one location to another), temporal (variability from one time period to another), and random (variability not directly attributed to space or time – but from some probability distribution). Consequently, all estimated fire regime and forest succession characteristics in BFOLDS will contain information about their spatial and/or temporal probabilities of occurrence, as well as estimates of their random variability.

In sum, BFOLDS is intended to explore and understand synoptic characteristics of large-scale forest landscape dynamics, especially with respect to their variability and probabilities of occurrence.

A generic view of the model

Conceptually, BFOLDS combines a set of spatial information on forest landscape composition, geo-climate, terrain, and soil with the best scientific logic and knowledge available on forest fire behaviour and forest succession to simulate the probabilistic characteristics of long-term fire regime and forest cover changes. Accordingly, a detailed explanation of how BFOLDS works can be organized by its input data, model logic, assumptions, and output information (Figure 2).

Input data consists of the spatial data layers (which will be described in detail later) that are fed into the model as formal definitions of the forest landscape. All or parts of these data may consist of user assumptions – either when data/information are incomplete or when users have to make choices in data classifications or data sources. Some input data layers enter the model via transformations (for example, forest cover type → forest fuel type) based either on published knowledge or user assumptions.

The model logic consists primarily of published scientific knowledge on forest fire and forest succession processes that is quantitative, spatially explicit, and in most cases, stochastic. BFOLDS' logic on forest fire processes is mechanistic and that on forest succession is empirical. Certain assumptions, also integral to the model logic, provide (a) linkages when scientific knowledge about modelled processes is inadequate (for example, fire extinguishment process) or (b) bounds on context for simulated processes (for example, incidence of non-fire forest disturbances and anthropogenic influences). Another group of assumptions used in BFOLDS simulations are controlled by users: (a) input data (for example, spatial fire weather patterns under climate change assumptions) and (b) model processes (for example, forest succession).

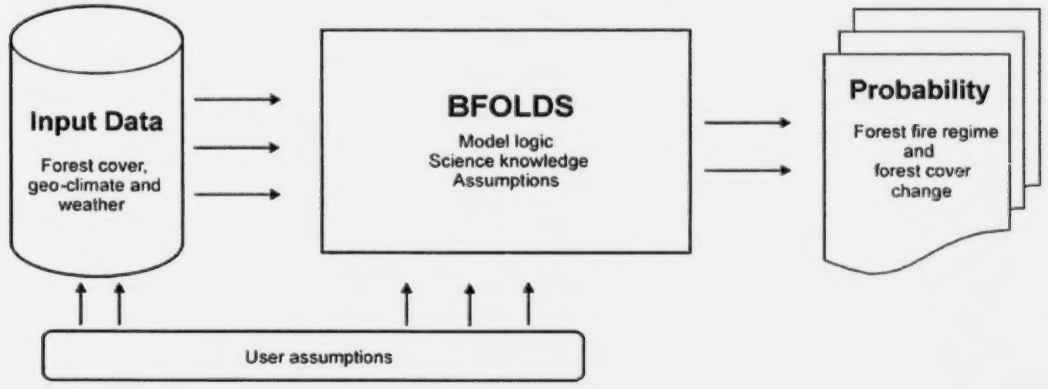

Figure 2. *A conceptual overview of major components in BFOLDS.*

The primary output of BFOLDS is simple: it informs of the incidence of fires and forest cover transitions for each 1-ha pixel of the simulated landscape during each simulation year. A variety of secondary output information (for example, fire sizes and number, forest cover trajectories, spatial distribution of forest age) can be generated by combining primary information spatially and temporally for a simulation period. A set of tertiary information on temporal, spatial, and random variability in forest landscape dynamics (for example, probabilities of fire occurrence, fire return interval, and old growth incidence) can be derived by combining the replicates of simulations, thereby capturing the stochasticity of modelled processes.

Sequence of BFOLDS processes

BFOLDS models forest landscape dynamics by sequentially simulating processes that occur during a forest fire season (a simulation year in the model), over many consecutive seasons (the simulation period) that represent the period for which landscape dynamics are estimated. Figure 3 illustrates a synopsis of the sequence of simulated processes in BFOLDS as a simplified overview. Each of those simulated process is described in greater detail with respect to its scientific principles, logic, and assumptions in subsequent sections.

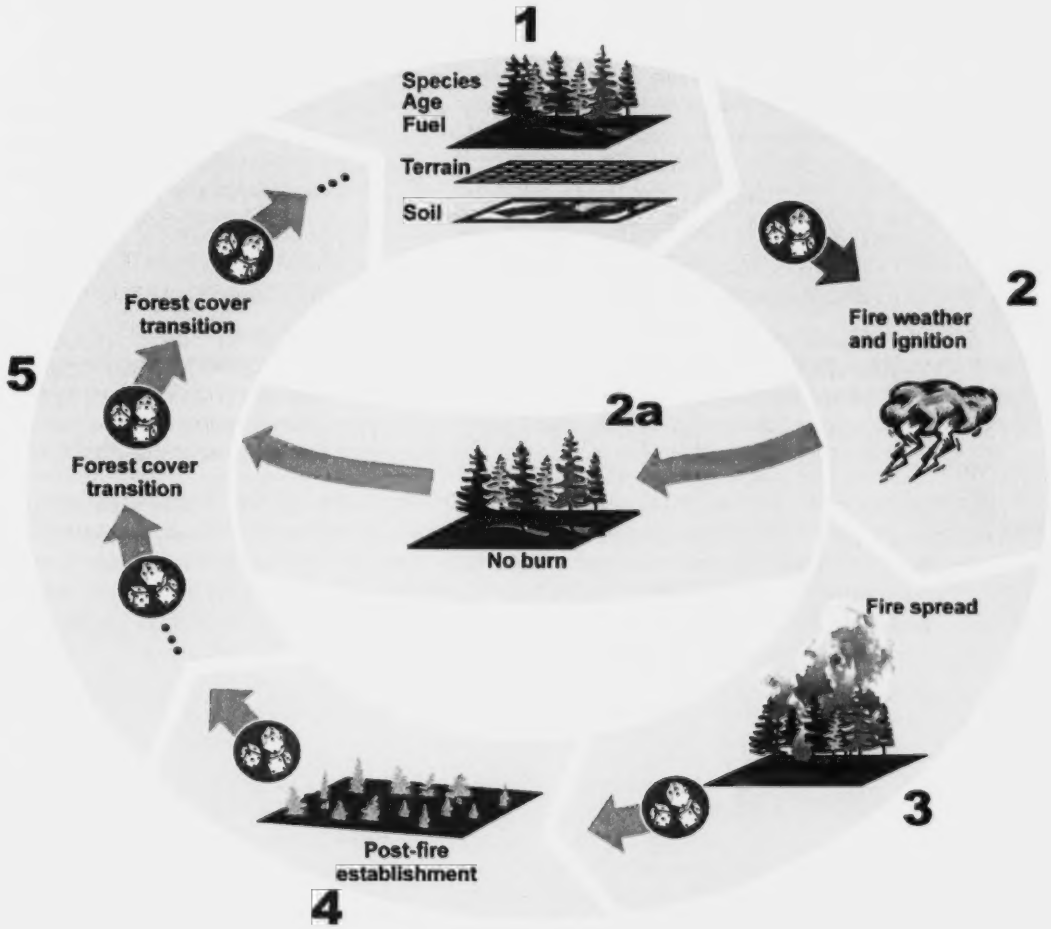

***Figure 3**. A summary of sequences in BFOLDS's simulations of forest fire regime and succession.*

The first step of this sequence is identifying how a forest landscape is seen by BFOLDS, which is as a spatial grid of 1 ha resolution where each 1-ha pixel contains information on the dominant forest cover type, age of the forest cover, fuel type (transformed from forest cover), slope, aspect, soil moisture regime, and soil nutrient regime.

Next, this landscape is probabilistically assigned weather conditions, which consist of precipitation, relative humidity, ambient temperature, as well as wind speed and direction, and these vary spatially across the landscape and with time (Step 2 in Figure 3). As such, each 1-ha pixel is probabilistically assigned daily weather conditions during a fire season. Subsequently, ignition points that simulate effective lightning strikes (which start natural forest fires) are also probabilistically assigned across the landscape, daily. Those 1-ha pixels receiving ignition points may or may not ignite based on the flammability of fuel *in situ*.

Pixels with forest cover that did not receive ignition points or burn because of fire spread and/or did not ignite due to nonflammability of fuel will succeed through time (Step 2a in Figure 3) until they burn by becoming flammable and receiving an ignition point or burning because of fire spread. Successful ignitions in the simulated landscape on any given day during the fire season are a result of the probabilities of fire weather, spatial distribution of ignition points, and the spatial distribution of flammable fuel.

Fires spread deterministically from ignited 1-ha pixels to neighbouring pixels (Step 3 in Figure 3) based on their characteristics (proximity, fuel content, slope, aspect) and prevailing fire weather at that time (wind, relative humidity, precipitation, temperature). This mechanistic fire spread continues spatially until a nonflammable pixel is reached and temporally until the weather is too wet. The forest cover in all burned pixels (regardless whether they are burned directly from ignitions or indirectly by fire spread from neighbours) is considered destroyed by fire. Spatial aggregates of conjoined burned pixels are designated as forest fires (which may encompass unburned pixels that eluded fire spread). Final sizes of simulated fires are therefore a result of spatial distribution of fuel and the temporal incidence of weather. Occurrence of simulated fires (how many, where, and when) and their characteristics (size, shape) within a landscape during a fire season depend on probabilities of fire ignition described in Step 2 and fire spread (spatial patterns of fuel availability and spatio-temporal patterns in fire weather) (Step 3 in Figure 2).

At the end of the fire season, when the weather is no longer conducive for forest fires, all burned pixels are assigned new forest cover types to simulate post-fire establishment of forest cover (Step 4 in Figure 3). This assignment is also probabilistic; based on the pre-burn forest cover and its age and soil nutrient and soil moisture conditions at each pixel. This assignment is based on empirical knowledge and/or user assumptions of forest succession probabilities, that is, it is not mechanistic (as opposed to the fire process simulation).

With establishment of new forest cover, burned pixels also are assigned new fuel types (transformed from forest cover information). However, these pixels will remain nonflammable for a 10-year period before they can reignite or reburn. Once they become flammable, they are subject to ignitions (Step 2 in Figure 3) during every subsequent fire season and, if they do not burn, they succeed through time into different forest cover (and fuel) types. Forest succession in the absence of fire is also simulated probabilistically, based on empirical and/or user assumptions (Step 5 in Figure 3).

This sequence is repeated until the end of the simulation period is reached.

Information generated by BFOLDS

Information on simulation processes within BFOLDS is tracked for each pixel, daily during the simulated fire season. The primary information tracked are: whether the pixel burned, date of burn, fire intensity, fuel type burned, and the source of burn, and, if the pixel did not burn, then the extant canopy cover, its age, and time since last burn (Figure 4).

At the end of a simulated year, this information is spatially aggregated to inform on the number and locations of fires, as well as their characteristics (for example, size, intensity, cover types burned). As well, the information on the unburned area of the simulated landscape is recorded (for example, composition of forest cover, forest canopy age, time since last burn). At the end of a simulation period, all annual information on fires is summarized to describe the landscape dynamics with respect to fire regime (for example, annual rates of burn, fire size distribution, fire return interval, spatial probability of fire), forest succession (for example, forest cover trajectories, spatial probability of compositional changes) and landscape aging (for example, canopy age composition, site age composition, spatial probability of canopy and site age classes).

This information is analogous to one set of fire history data (an assembly of fire history maps, typically with fire polygons and dates of fire occurrences). Because BFOLDS model logic contains many interacting probabilities, replicated simulation periods are not likely to result in the same fire regime or forest succession information.

Therefore, it is possible to capture the probabilistic character of fire and forest succession processes by combining the information generated from replicates, across simulated periods. This enables the estimates of variability in fire regime and other landscape processes either as common statistical parameters (for example, means, medians, ranges, variances) or as probability distributions.

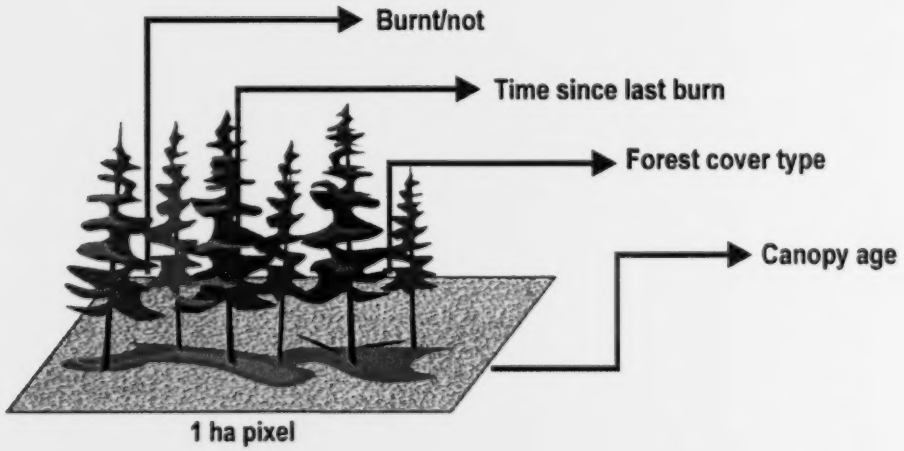

Figure 4. *A summary of primary information generated by BFOLDS simulations annually for each 1-ha pixel of a landscape.*

Furthermore, all information generated by BFOLDS is spatially (to 1 ha pixel level) and temporally (yearly) explicit. This makes it possible to analyze spatial and temporal patterns as well as variability in space and time. Information on variability (random, spatial, and temporal) and probabilities (spatial and temporal) are emergent properties of the simulation process, not results of *a priori* assumptions or necessarily evident from input information.

The most valuable information generated by BFOLDS is the variability in forest landscape dynamics. This is possible because BFOLDS simulations capture various probabilistic processes in fire and forest succession and reveal the emerging properties, which are not readily evident from empirical observations.

How does BFOLDS simulate forest fires?

Background

In the strictest sense, 'natural' fires in boreal forests are those started by lightning that burn a forest landscape that is not anthropogenically altered and are not artificially suppressed (Cui and Perera 2006). Such fires and their effects on forested landscapes provide a window to understanding the natural forest fire regime. Therefore, in keeping with its goal to explore the natural range of possibilities of the boreal fire regime, BFOLDS simulates only lightning-caused ignitions. As well, simulation of the other two major process steps in a fire (fire spread and extinguishment) is also decided only by natural factors: fuel types, topography, and weather conditions – human activities, such as fire suppression and fuel modification, are not simulated.

BFOLDS simulates fires for every day of a fire season, and for every year of a fire simulation period, consecutively. During any given day of a fire season, multiple fires may concurrently ignite, spread, and extinguish across the simulated forest landscape, as guided by simulated temporal patterns of local weather and spatial patterns of fuel availability. Fire simulation is spatially explicit, responding to heterogeneity and juxtaposition of fuel, topography, and weather conditions. As such, the major information groups used in fire simulation are weather and forest fuel. Topography is also used, but only as a modifier of rate of fire spread. Below we describe the details of the fire weather and forest fuel information because these provide the basis for fire ignition, spread, and extinguishment of fire event simulation in BFOLDS.

Weather

(a) Use of weather information

Weather parameters are the most fundamental and important information in BFOLDS fire simulation processes. BFOLDS uses weather in the format of the Canadian Forest Fire Weather Index System (FWI system) for fire simulation. The FWI system (Van Wagner and Pickett 1985) uses weather parameters – temperature, relative humidity, rain, and wind – to derive six major synthetic components that describe condition of fuel and expected fire spread (Figure 5). The first three components are fuel moisture codes, i.e., numeric ratings of potential moisture content in forest fuel. The remaining three components are fire behaviour indices, which represent the rate of fire spread, the fuel available for combustion, and the frontal fire intensity.

- *Fine Fuel Moisture Code* (FFMC) is a numeric rating of the moisture content of litter and other cured fine fuels. It is an indicator of the relative ease of ignition and the flammability of fine fuel on the forest floor.
- *Duff Moisture Code* (DMC) is a numeric rating of the average moisture content of loosely compacted organic layers of moderate depth over soil. This code indicates potential fuel consumption in moderate duff layers and medium-size woody material.
- *Drought Code* (DC) is a numeric rating of the average moisture content of deep, compact organic layers on the forest floor, which is a useful indicator of seasonal drought effects on forest fuels and the potential degree of smouldering in deep duff layers and large logs.
- *Initial Spread Index* (ISI) is a numeric rating of the expected rate of fire spread. It combines the effects of wind and the FFMC on rate of spread without the influence of variable quantities of fuel.
- *Buildup Index* (BUI) is a numeric rating of the total amount of fuel available for combustion as a combination of DMC and DC.
- *Fire Weather Index* (FWI) is a synoptic numeric rating of fire intensity that encapsulates all other indices via ISI and BUI.

The components are calculated based on consecutive daily means of temperature, relative humidity, wind speed, and cumulative rainfall. A detailed description of these calculations within BFOLDS is given below. Table 1 provides descriptions for the parameters used in the equations.

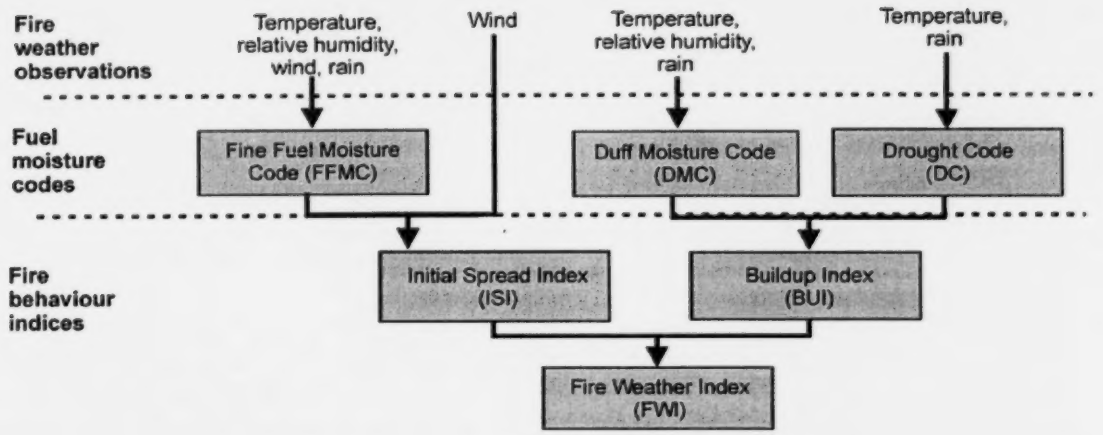

Figure 5. Structure of the Canadian Forest Fire Weather Index System (FWI system) (from http://cwfis.cfs.nrcan.gc.ca/en/background/bi_FWI_summary_e.php).

Table 1. Components of the Canadian Forest Fire Weather Index System used in BFOLDS fire simulation equations

Weather		Fine fuel moisture code (FFMC)		Duff moisture code (DMC)		Drought code (DC)		Initial spread index (ISI) Buildup index (BUI) Fire weather index (FWI)	
Parameter	Description	Parameter	Description	Parameter	Description	Parameter	Description	Parameter	Description
T	Noon temperature, °C	m_0	Fine fuel moisture content from previous day	M_0	Duff moisture content from previous day	Q	Moisture equivalent of DC, units of 0.254 mm	f(W)	Wind function
H	Noon relative humidity, %	m_r	Fine fuel moisture content after rain	M_r	Duff moisture content after rain	Q_0	Moisture equivalent of previous day's DC	f(F)	Fine fuel moisture function
W	Noon wind speed, km/h	m	Fine fuel moisture content after drying	M	Duff moisture content after drying	Q_r	Moisture equivalent after rain	f(D)	Duff moisture function
r_0	Rainfall accumulation in open, measured measured once daily at noon, mm	E_d	Fine fuel EMC for drying	K	Log drying rate in DMC, $\log_{10}$M/day	V	Potential evapotranspiration, units of 0.254 mm water/day	R	Initial spread index (ISI)
r_f	Effective rainfall, FFMC	E_w	Fine fuel EMC for wetting	L_e	Effective day length in DMC, hours	L_f	Day length adjustment in DC	U	Buildup index (BUI)
r_e	Effective rainfall, DMC	k_0	Intermediate step in calculation of k_d	b	Slope variable in DMC rain effect	D_0	Previous day's DC	B	FWI (intermediate form)
r_d	Effective rainfall, DC	k_d	Log drying rate, FFMC, $\log_{10}$m/day	P_0	Previous day's DMC	D_r	DC after rain	S	FWI (final form)
		k_l	Intermediate step in calculation of k_w	P_r	DMC after rain	D	DC		
		k_w	Log wetting rate, $\log_{10}$m/day	P	DMC				
		F_0	Previous day's FFMC						
		F	FFMC						

1. FFMC equations and procedures

$$m_0 = 147.2(101 - F_0)/(59.5 + F_0) \tag{1}$$

$$r_f = r_0 - 0.5, \qquad r_0 > 0.5 \tag{2}$$

$$m_r = m_0 + 42.5 r_f \left[e^{-100/(251 - m_0)} \right] \left(1 - e^{-6.93/r_f}\right), \quad m_0 \le 150 \tag{3a}$$

$$m_r = m_0 + 42.5 r_f \left[e^{-100/(251 - m_0)} \right] \left(1 - e^{-6.93/r_f}\right) + 0.0015(m_0 - 150)^2 r_f^{0.5}, \quad m_0 > 150 \tag{3b}$$

$$E_d = 0.942 H^{0.679} + 11 e^{(H-100)/10} + 0.18(21.1 - T)(1 - e^{-0.115H}) \tag{4}$$

$$E_w = 0.618 H^{0.753} + 10 e^{(H-100)/10} + 0.18(21.1 - T)(1 - e^{-0.115H}) \tag{5}$$

$$k_0 = 0.424\left[1 - (H/100)^{1.7}\right] + 0.0694 W^{0.5}\left[1 - (H/100)^{8}\right] \tag{6a}$$

$$k_d = k_0 \times 0.581 e^{0.0365T} \tag{6b}$$

$$k_l = 0.424\left[1 - \left(\frac{100 - H}{100}\right)^{1.7}\right] + 0.0694 W^{0.5}\left[1 - \left(\frac{100 - H}{100}\right)^{8}\right] \tag{7a}$$

$$k_w = k_l \times 0.581 e^{0.0365T} \tag{7b}$$

$$m = E_d + (m_0 - E_d) \times 10^{-k_d} \tag{8}$$

$$m = E_w - (E_w - m_0) \times 10^{-k_w} \tag{9}$$

$$F = 59.5(250 - m)/(147.2 + m) \tag{10}$$

Based on the above, FFMC is calculated as follows:

1. Previous day's F becomes F_0.
2. Calculate m_0 from F_0 by Equation 1.
3. a. If r_0>0.5, calculate r_f by Equation 2.
   b. Calculate m_r from r_f and m_0 by Equation 3a or 3b.
   - o if $m_0 \le 150$, use Equation 3a.
   - o if m_0>150, use Equation 3b.

c. Then, m_r becomes the new m_0.

4. Calculate E_d by Equation 4.
5. a. If $m_0 > E_d$, calculate k_d by Equations 6a and 6b.
   b. Calculate m by Equation 8.
6. If $m_0 < E_d$, calculate k_w by Equations 7a and 7b.
7. a. If $m_0 < E_w$, calculate k_w by Equations 7a and 7b.
   b. Calculate m by Equation 9.
8. If $E_d \geq m_0 \geq E_w$, let $m = m_0$.
9. Calculate F from m by Equation 10. This is today's FFMC.

2. DMC equations and procedures

$$r_e = 0.92 r_0 - 1.27, \quad r_0 > 1.5 \tag{11}$$

$$M_0 = 20 + e^{(5.6348 - P_0/43.43)} \tag{12}$$

$$b = 100/(0.5 + 0.3P_0), \quad P_0 \leq 33 \tag{13a}$$

$$b = 14 - 1.3 \ln P_0, \quad 33 < P_0 \leq 65 \tag{13b}$$

$$b = 6.2 \ln P_0 - 17.2, \quad P_0 > 65 \tag{13c}$$

$$M_r = M_0 + 1000 r_e / (48.77 + b r_e) \tag{14}$$

$$P_r = 244.72 - 43.43 \ln(M_r - 20) \tag{15}$$

$$K = 1.894(T + 1.1)(100 - H) L_e \times 10^{-6} \tag{16}$$

$$P = P_0 (or\ P_r) + 100K \tag{17}$$

Based on the above, the DMC is calculated as follows:

1. Previous day's P becomes P_0.
2. a. If $r_0 > 1.5$, calculate r_e by Equation 11.
   b. Calculate M_0 from P_0 by Equation 12.
   c. Calculate b by most appropriate of Equations 13a, 13b, or 13c.
   d. Calculate M_r by Equation 14.
   e. Convert M_r to P_r by Equation 15. P_r becomes new P_0.

3. Use L_e from Table 2 below.

***Table 2**. Effective daylength (L_e) for duff moisture code.*

	Month											
	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
L_e	6.5	7.5	0.9	12.8	13.9	13.9	12.4	10.9	9.4	8.0	7.0	6.0

4. Calculate K by Equation 16.

5. Calculate P from P_0 (or P_r) by Equation 17. This is DMC for the simulation day.

Three restrictions are imposed on the use of the DMC equations:

1. Equations 11 to 15 are not used unless r_0>1.5
2. $P_r \geq 0$ always: if P_r <0 from step 2e, then let P_r =0.
3. $T \geq -1.1$ always in equation 15: If T<-1.1, let T=-1.1.

3. DC equations and procedures

$$r_d = 0.83 r_0 - 1.27, \quad r > 2.8 \tag{18}$$

$$Q_0 = 800 e^{-D_0/400} \tag{19}$$

$$Q_r = Q_0 + 3.937 r_d \tag{20}$$

$$D_r = 400 \ln(800/Q_r) \tag{21}$$

$$V = 0.36(T + 2.8) + L_f \tag{22}$$

$$D = D_0 (or\ D_r) + 0.5V \tag{23}$$

Based on the above, DC is calculated as follows:

1. Previous day's D becomes D_0.

2. a. If r_0>2.8, calculate r_d by Equation 18.
   b. Calculate Q_0 from D_0 by Equation 19.
   c. Calculate Q_r by Equation 20.
   d. Convert Q_r to D_r by equation 21 and D_r becomes D_0.

3. Use L_f from Table 3 below.
4. Calculate V by Equation 22.
5. Calculate D from D_0 (or D_r) by Equation 23. This is DC for the simulation day

Table 3. *Daylength factors (Lf) for drought code.*

	Month											
	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
L_f	1.6	-1.6	-1.6	0.9	3.8	5.8	6.4	5.0	2.4	0.4	-1.6	-1.6

Four restrictions are imposed on the use of the DC equations:

1. Equations 18 to 21 are not used unless r_0>2.8.
2. $D_r \geq 0$ always: if $D_r \leq 0$, then let $D_r = 0$.
3. In Equation 22, if T<-2.8, then let T=-2.8.
4. $V \geq 0$ always: if $V < 0$, then let V=0.

4. ISI equations and procedures

$$f(W) = e^{0.05039W} \tag{24}$$

$$f(F) = 91.9e^{-0.1386m}\left[1 + m^{5.31}/(4.93\times10^7)\right] \tag{25}$$

$$R = 0.208 \times f(W) f(F) \tag{26}$$

5. BUI equations and procedures

$$U = 0.8PD/(P+0.4D), \quad P \leq 0.4D \tag{27}$$

$$U = P - [1 - 0.8D/(P+0.4D)][0.92 + (0.0114P)^{1.7}], \quad P > 0.4D \tag{28}$$

From above, ISI and BUI are calculated as follows:

1.Calculate f(W) and f(F) by equations 24 and 25.

2.Calculate R by equation 26. This is ISI for the simulation day.

3.Calculate U by equation 27a if P≤0.4D, or Equation 27b if P>0.4D. This is BUI for the simulation day.

(b) Input of weather information

BFOLDS uses weather information at 1 ha resolution. A spatial grid of weather parameters in BFOLDS is created using point data (that represent observed data from extant weather stations, simulated data for extant weather stations, or simulated data for simulated weather stations) that users provide. The weather parameters interpolated are wind speed, wind direction, FFMC, DMC, and BUI. A smooth cubic spline interpolation algorithm is used to interpolate the point data for each 1-ha pixel across the simulation area. The algorithm is from Flannigan and Wotton (1989) as detailed below.

An interpolated index Z at a location with a coordinate of (x_j, y_j) can be calculated as:

$$Z(x_j, y_j) = \alpha_0 + \alpha_1 x_j + \alpha_2 y_j + \sum_{k=1}^{n} \beta_k \phi(r_{ij}) \quad (1)$$

where

$$r_{ij} = \left[(x_i - x_j)^2 + (y_i - y_j)^2 \right]^{1/2} \quad (2)$$

and

$$\phi(r_{ij}) = r_{ij}^2 \ln(r_{ij}) \quad (3)$$

The coefficients $\alpha(\alpha_0, \alpha_1, \alpha_2)$ and $\beta(\beta_1, \beta_2, \ldots, \beta_n)$ can be found by solving the linear system:

$$\begin{bmatrix} \overset{S}{\phi} & A \\ A^T & 0 \end{bmatrix} \begin{bmatrix} \overset{B}{\beta} \\ \alpha \end{bmatrix} = \begin{bmatrix} \overset{C}{Y} \\ 0 \end{bmatrix} \quad (4)$$

where ϕ is a symmetric n by n matrix whose values are the $\phi(r_{ij})$ for all combinations of weather data points (e.g., i=1 to n and j=1 to n) and A is an n by 3 matrix for components of the first part of the equation (1) for all weather data points

$$\begin{bmatrix} 1 & x_1 & y_1 \\ 1 & x_2 & y_2 \\ \vdots & \vdots & \vdots \\ 1 & x_n & y_n \end{bmatrix} \quad (5)$$

And Y is an n by 1 matrix of the observed values. The matrix S is an (n+3) by (n+3) matrix with every value on the main diagonal equal to 0. The solution of β and α is

$$B = S^{-1}C \quad (6)$$

Forest fuel

BFOLDS uses the forest fuel information based on the Canadian Forest Fire Behaviour Prediction System (FBP system) (Forestry Canada Fire Danger Group 1992, Wotton et al. in press), which classifies fuel types for all Canadian forest types, and is used to predict potential forest fire behaviour. It defines a fuel type as "a fuel complex of sufficient homogeneity and extending over an area of sufficient size that equilibrium fire behaviour can be maintained over a considerable time period". The FBP system identifies 16 discrete fuel types for Canadian forests, grouped by the major forest overstory types (coniferous, deciduous, and mixedwood), post-management conditions (slash), and non-forested area (Table 4).

BFOLDS uses fuel information at 1 ha resolution. A spatial grid of fuel type is created by transforming forest cover information using forest cover–fuel type conversion rules that users adopt based on the FBP system (Forestry Canada Fire Danger Group 1992).

Table 4. *Forest fire behaviour prediction system fuel types used in BFOLDS.*

Group	Identifier	Descriptive name
Coniferous	C-1	Spruce-lichen woodland
	C-2	Boreal spruce
	C-3	Mature jack or lodgepole pine
	C-4	Immature jack or lodgepole pine
	C-5	Red or white pine
	C-6	Conifer plantation
Deciduous	D 1	Leafless aspen
Mixedwood	M-1	Boreal mixedwood - leafless
	M-2	Boreal mixedwood - green
	M-3	Dead balsam fir mixedwood - leafless
	M-4	Dead balsam fir mixedwood - green
Slash	S-1	Jack or lodgepole pine slash
	S-2	White spruce-balsam fir slash
Open	O-1a	Matted grass
	O-1b	Standing grass

Principles of simulating fire behaviour

BFOLDS utilizes the principles of the FBP system (Forestry Canada Fire Danger Group 1992, Wotton et al. in press) to simulate all processes of fire within its model structure by combining information on fuel types, weather, topography, and geography, over time (Figure 6).

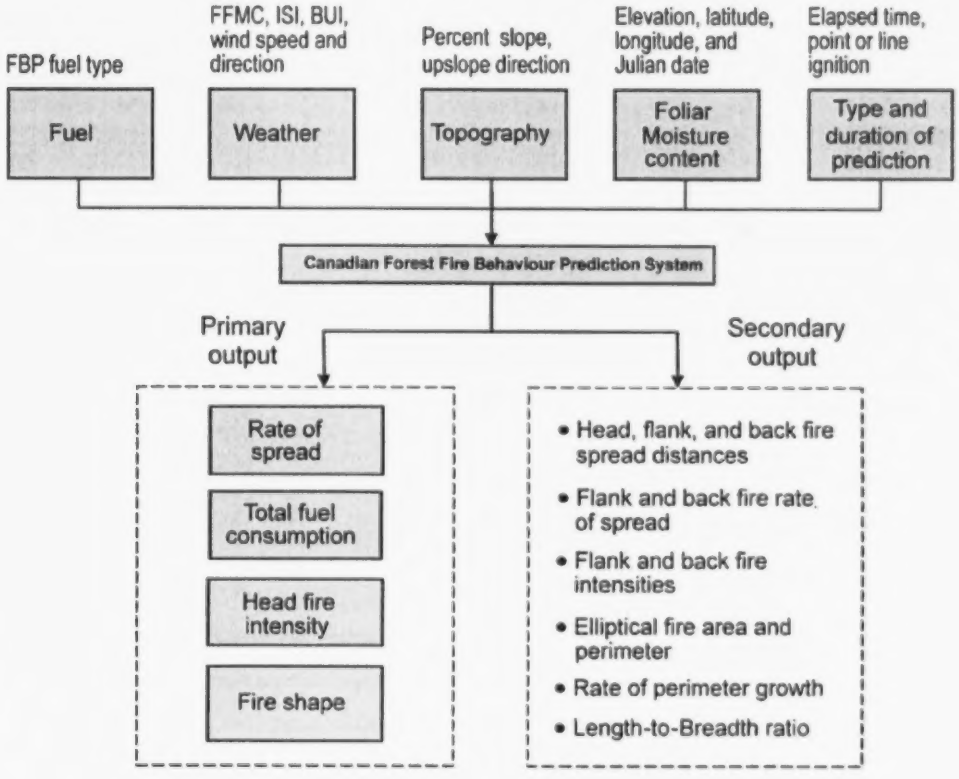
FBP fuel type
FFMC, ISI, BUI, wind speed and direction
Percent slope, upslope direction
Elevation, latitude, longitude, and Julian date
Elapsed time, point or line ignition
Fuel
Weather
Topography
Foliar Moisture content
Type and duration of prediction
Canadian Forest Fire Behaviour Prediction System
Primary output
Secondary output
Rate of spread
Total fuel consumption
Head fire intensity
Fire shape
• Head, flank, and back fire spread distances
• Flank and back fire rate of spread
• Flank and back fire intensities
• Elliptical fire area and perimeter
• Rate of perimeter growth
• Length-to-Breadth ratio

Figure 6. *An overview of the Canadian Forest Fire Behaviour Prediction System.*

(a) Rate of fire spread estimation in FBP

i. Surface fuel consumption

Fuel consumption in BFOLDS is addressed as two distinct sections: surface fuel consumption and total consumption. Surface fuel consumption (SFC) is used in determining the onset of crown fire initiation. Total fuel consumption includes the crown fuels consumed, which is calculated after the degree of crown burn is estimated (described in a later section). The following equations are used to calculate SFC for different fuel types (where SFC is the surface fuel consumption; FFMC is the fine fuel moisture code value; PC and PH are percent conifer and percent hardwood composition, respectively; and GFL is the grass fuel load (standard value 0.3 kg/m^2).

C-1:

$$SFC = 0.75 + 0.75 \times \left[1 - e^{-0.23(FFMC-84)}\right]^{0.5} \quad if \quad FFMC > 84$$
$$SFC = 0.75 - 0.75 \times \left[1 - e^{-0.23(FFMC-84)}\right]^{0.5} \quad if \quad FFMC \leq 84$$

C-2, M-3 and M-4: $SFC = 5.0 \times \left[1 - e^{(-0.0115 \times BUI)}\right]^{1.0}$

C-3 or C-4: $SFC = 5.0 \times \left[1 - e^{(-0.0164 \times BUI)}\right]^{2.24}$

C-5 or C-6: $SFC = 5.0 \times \left[1 - e^{(-0.0149 \times BUI)}\right]^{2.48}$

D-1: $SFC = 1.5 \times \left[1 - e^{(-0.0183 \times BUI)}\right]$

M-1 or M-2: $SFC = \left[\frac{PC}{100} \times (SFC\ for\ C\text{-}2)\right] + \left[\frac{PH}{100} \times (SFC\ for\ D\text{-}1)\right]$

O-1: $SFC = GFL$

S-1: $SFC = 4.0 \times \left[1 - e^{(-0.025 \times BUI)}\right]$

S-2: $SFC = FFC = 10.0 \times \left[1 - e^{(-0.013 \times BUI)}\right]$

ii. Initial rate of spread

For all fuel types except mixedwood initial rate of spread is calculated, using parameters in Table 5, as:

$$RSI = a \times \left[1 - e^{(-b \times ISI)}\right]^c$$

Table 5. *Rate of spread parameter values for all fuel types except mixedwood.*

Fuel types	a	b	C
C-1	90	0.0649	4.5
C-2	110	0.0282	1.5
C-3	110	0.0444	3.0
C-4	110	0.0293	1.5
C-5	30	0.0697	4.0
C-6	30	0.0800	3.0
D-1	30	0.0232	1.6
S-1	75	0.0297	1.3
S-2	40	0.0438	1.7
O-1a	190	0.0310	1.4
O-1b	250	0.0350	1.7

For M-1:

$$RSI = \left[\frac{PC}{100} \times (RSI \ for \ C\text{-}2)\right] + \left[\frac{PH}{100} \times (RSI \ for \ D\text{-}1)\right]$$

For M-2:

$$RSI = \left[\frac{PC}{100} \times (RSI \ for \ C\text{-}2)\right] + 0.2 \times \left[\frac{PH}{100} \times (RSI \ for \ D\text{-}1)\right]$$

For M-3:

$$RSI = \frac{PDF}{100} \times RSI_{M-3(100\%)} + \left(1 - \frac{PDF}{100}\right) \times RSI_{D-1}$$

Where $RSI_{M-3(100\%)}$ is given by

$$RSI_{M-3(100\%)} = 120 \times \left[1 - e^{(-0.0572 \times ISI)}\right]^{1.4}$$

For M-4:

$$RSI = \frac{PDF}{100} \times RSI_{M-4(100\%)} + 0.2 \times \left(1 - \frac{PDF}{100}\right) \times RSI_{D-1}$$

Where $RSI_{M-4(100\%)}$ is given by

$$RSI_{M-4(100\%)} = 100 \times \left[1 - e^{(-0.0404 \times ISI)}\right]^{1.48}$$

Where RSI is the initial rate of spread; PC and PH are percent conifer and percent hardwood composition, respectively; PDF is percent dead fir.

For plantation fuel types: C-6

The rate of spread for this fuel type is estimated differently and is discussed in a later section.

For grass fuel types:

$$ROS = a \times \left[1 - e^{(-b \times ISI)}\right]^{c} \times CF$$

$$CF = 0.005 \times \left(e^{0.061 \times CUR} - 1.0\right) \qquad C < 58.8$$
$$CF = 0.176 + 0.02 \times (CUR - 58.8) \qquad C \geq 58.8$$

where ROS is the surface fire rate of spread; a, b and c are fuel type-specific constants from Table 5; and CF is the grass curing coefficient and C is the degree of curing (%).

iii. Fire spread rate modified by slope effect

Percent ground slope:

$$\text{\% ground slope} = \frac{Elevation\ rise}{Horizontal\ ground\ dist.} \times 100$$

Spread factor:

$$SF = e^{3.533\times\left(\frac{GS}{100}\right)^{1.2}} \quad if \quad GS < 60$$
$$SF = 6.78 \quad if \quad GS \geq 60$$

where GS is the percent slope, SF is the spread factor.

Slope adjusted zero wind rate of spread:

$$RSF = RSZ \times SF$$

where RSF is the slope adjusted zero wind rate of spread; RSZ is the zero wind rate of spread.

ISI with slope influence and zero wind:

$$ISF = \frac{\ln\left[1-\left(\frac{RSF}{a}\right)^{\frac{1}{c}}\right]}{-b} \quad if \quad \left[1-\left(\frac{RSF}{a}\right)^{\frac{1}{c}}\right] \geq 0.01$$

$$ISF = \frac{\ln(0.01)}{-b} \quad if \quad \left[1-\left(\frac{RSF}{a}\right)^{\frac{1}{c}}\right] < 0.01$$

where ISF is the ISI with slope influence and zero wind; RSF is the slope adjusted zero wind rate of spread; and a, b, and c are fuel type-specific rate of spread equation constants.

The above ISF will not work for M-1, M-2, or O-1 fuel types.

For M-1 and M-2:

$$ISF = \frac{PC}{100} \times ISF_{C-2} + \left[\left(1 - \frac{PC}{100} \right) \times ISF_{D-1} \right]$$

For O-1:

$$ISF = \frac{\ln\left[1 - \left(\frac{RSF}{CF \times a}\right)^{\frac{1}{c}}\right]}{-b} \qquad if \quad \left[1 - \left(\frac{RSF}{CF \times a}\right)^{\frac{1}{c}}\right] \geq 0.01$$

$$ISF = \frac{\ln(0.01)}{-b} \qquad if \quad \left[1 - \left(\frac{RSF}{a}\right)^{\frac{1}{c}}\right] < 0.01$$

- Slope equivalent wind speed (WSE)

$$WSE = \frac{\ln\left[\frac{ISF}{0.208 \times f(F)}\right]}{0.05039}$$

where f(f) is the FFMC function from the ISI equation as follows:

$$f(F) = 91.9 \times e^{(-0.1386 \times m)} \times \left[1 + \frac{m^{5.31}}{4.93 \times 10^7}\right]$$

where

$$m = \frac{147.2 \times (101 - FFMC)}{59.5 + FFMC}$$

$$WSX = [WS \times \sin(WAZ)] + [WSE \times \sin(SAZ)]$$
$$WSY = [WS \times \cos(WAZ)] + [WSE \times \cos(SAZ)]$$

$$WSV = \sqrt{(WSX^2 + WSY^2)}$$

$$RAZ = \arccos\left(\frac{WSY}{WSX}\right)$$

where WSX is the resultant vector magnitude in the x direction; WSY is the resultant vector magnitude in the y direction; WAZ is the wind azimuth (direction); SAZ is the uphill slope azimuth (direction); WSV is the net effective wind speed; and RAZ is the net effective wind direction.

If WSX<0, then RAZ=360-RAZ

- ISI equation:

$$ISI = 0.208 \times f(W) \times f(F)$$

where

$$f(W) = e^{0.05039 \times WSV}$$

iv. Spread rate modified by fuel buildup effect

- Buildup effect (BE) is calculated using the values provided in Table 6 as follows:

$$BE = e^{\left[50 \times \ln(q) \times \left(\frac{1}{BUI} - \frac{1}{BUI_0}\right)\right]}$$

where BUI_0 is the average BUI for the fuel type. The value of BUI_0 and q are listed in Table 6.

Table 6. *Values of buildup index (BUI0), q, and maximum buildup effect (BE) for each fuel type.*

Fuel types	BUI_0	q	Max. BE
C-1	72	0.90	1.076
C-2	64	0.70	1.321
C-3	62	0.75	1.261
C-4	66	0.80	1.184
C-5	56	0.80	1.220
C-6	62	0. 80	1.197
D-1	32	0.90	1.179
M-1	(50)*	(0.80)	1.250
M-2	(50)	(0.80)	1.250
M-3	(50)	(0.80)	1.250
M-4	(50)	(0.80)	1.250
S-1	38	0.75	1.460
S-2	63	0.75	1.256
O-1a		1	1.000
O-1b		1	1.000

*Values in parentheses have been set arbitrarily

ROS=RSI×BE

v. Fire spread rate modified by crowning effect

- Critical surface fire intensity (CSI) for crowning is calculated using the parameters in Table 7 as follows:

$$CSI = 0.001 \times CBH^{1.5} \times (460 + 25.9 \times FMC)^{1.5}$$

where CBH is the height above ground that the live crown base begins and FMC is the foliar moisture content.

Table 7. Crown base height (CBH) and crown fuel load (CFL) for fuel types subject to crowning.

Fuel types	CBH (m)	CFL (kg/m²)
C-2	3	0.80
C-3	8	1.15
C-4	4	1.20
C-5	18	1.20
C-6	7	1.80
M-1	6	0.80
M-2	6	0.80
M-3	6	0.80
M-4	6	0.80

- The critical surface fire spread rate (RSO):

$$RSO = \frac{CSI}{300 \times SFC}$$

where SFC is the surface fuel consumption.

- Crown fraction burned (CFB):

$$CFB = 1 - e^{-0.23 \times (ROS - RSO)}$$

where ROS is the predicted fire rate of spread (m/min).

vi. Conifer plantation (C-6) spread rate

- Foliar moisture effect on crown fire spread

$$FME = \frac{(1.5 - 0.00275 \times FMC)^{4.0}}{460 + (25.9 \times FMC)} \times 1000$$

- Conifer plantation (C-6) spread rate

$$RSI = 30 \times \left[1 - e^{(-0.08 \times ISI)}\right]^{3.0}$$

$RSS = RSI \times BE$

$$RSC = 60 \times \left(1 - e^{-0.0497 \times ISI}\right)^{1.00} \times \frac{FME}{FME_{avg}}$$

$ROS = RSS + CFB \times (RSC - RSS)$

Where RSI is the intermediate surface fire spread rate; RSS is the surface fire spread rate; RSC is the crown fire spread rate; FME is the foliar moisture effect; and FME_{avg} is 0.778; ROS is the final spread rate.

(b) Final fuel consumption estimation in FBP

i. Crown fuel consumption (CFC) (kg/m^2):

$CFC = CFL \times CFB$

ii. Total fuel consumption (TFC) (kg/m^2):

$TFC = SFC + CFC$

Where SFC is the surface fuel consumption (kg/m^2); CFB is the crown fraction burned.

(c) Fire intensity estimation in FBP

Predicted fire intensity (kW/m):

$FI = 300 \times TFC \times ROS$

(d) Elliptical fire growth estimation in FBP

i. Back fire spread rate

- The back fire wind function: Bf(W)

$$Bf(W) = e^{-0.05039 \times WSV}$$

Where WSV is wind speed vector.

- ISI associated with the back fire spread rate

$$BISI = 0.208 \times Bf(W) \times f(F)$$

Where f(F) is the FFMC function.

- Back fire spread rate (m/min)

$$BROS = a \times \left(1 - e^{-b \times BISI}\right)^{c} \times BE$$

Where a, b, and c are fuel type-specific constants and BE is the buildup effect.

ii. Length-to-breadth (LB) ratio:

- For all fuel types except grass fuel types:

$$LB = 1.0 + 8.729 \times \left[1 - e^{-0.030 \times WSV}\right]^{2.155}$$

- For grass fuel types:

$$LB = 1.1 \times WSV^{0.464}$$

iii. Flank rate of spread (FROS):

$$FROS = \frac{ROS + BROS}{2 \times LB}$$

iv. Rate of spread (ROS) in any direction (Catchpole et al. 1982):

$$ROS(\theta) = \frac{ROS - BROS}{2 \times \cos\theta} + \frac{ROS + BROS}{2 \times \cos\theta} \times \left(\frac{FROS \times \cos\theta \times \left[FROS^2 \times \cos^2\theta + (ROS \times BROS) \times \sin^2\theta\right]^{\frac{1}{2}} - \frac{\left(ROS^2 - BROS^2\right)}{4} \times \sin^2\theta}{FROS^2 \times \cos^2\theta + \left(\frac{ROS + BROS}{2}\right)^2 \times \sin^2\theta} \right)$$

Where θ is angle in radian, ROS is rate of spread, BROS is the rate of spread of backfire, and FROS is the rate of spread of flank fire (as illustrated in Figure 7).

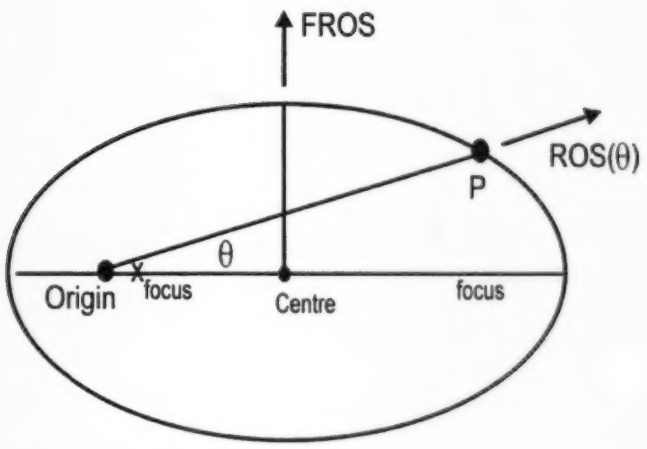

Figure 7. *Illustration of fire rate of spread directions.*

Fire simulation process in BFOLDS

The BFOLDS fire simulation process has three major steps: ignition of fires, spread of ignited fires, and extinguishment of fires. These steps determine all simulated fire events within a day, a fire season, and over a simulation period. No presumptions guide the simulations of, for example, location, size and shape of simulated fire events, total number of fires, area burned, and fire size distribution during a fire season or a simulation period: these are properties that emerge solely as the result of mechanistic and probabilistic interactions among fire weather and fuel types that inform the model via input data.

Fire ignition

The fire ignition step represents the process of ignition of lightning-caused fires in a forest landscape. It provides daily opportunities for fires to ignite during the fire season by simulating the effect of lightning strikes across a landscape. Since the scientific state of knowledge and data available do not permit mechanistic simulations of lightning storms and the polarity of their ground lightning strikes, BFOLDS resorts to a stochastic simulation of successful lightning strikes, which are statistically derived. Simply, it uses a data set of daily successful ignitions for a fire season (by Julian day), for many fire seasons. This data is input by the user, as either empirical observations and/or assumptions.

BFOLDS assumes that the probability of occurrence of lightning-caused fires for any given day stems from a Poisson distribution. The input data is the mean number of fire-causing lightning strikes for that day, for the simulated landscape. The potential number of new lightning fires that day is a Poisson-distributed random variable with that mean. The actual number of new lightning fires that day might be lower, depending on the fuel moisture conditions. If the DMC over the entire landscape is below a threshold, then no ignitions occur that day. If some or all of the landscape has sufficiently high DMC, then the new ignitions are placed on the landscape.

As a default, the model assumes that these new fires are randomly (from a uniform distribution) placed across the landscape. However, users may change this assumption, and insert a spatial biasing pattern of their choice, so every pixel in the landscape does not have an equal probability of an ignition placement. Each burnable 1-ha pixel is statistically eligible to receive a fire-causing lightning strike. Any pixels that are inherently non-burnable (for example, water bodies and bedrock) would never ignite, so any potential fires distributed on those pixels are immediately redistributed elsewhere (sampling with replacement). Any pixels that are inherently burnable but not *currently* burnable (for example, immediately after a fire or currently too wet) are not redistributed (sampling without replacement); those potential fires are not realized. Any inherently burnable 1-ha pixel that is sufficiently dry will ignite. This fire ignition process is repeated daily through the fire season.

Fire spread

The spread of ignited fires is simulated during the fire spread process step of fire simulation in BFOLDS. It is a completely mechanistic process that is anchored in the principles of the FBP system (Forestry Canada Fire Danger Group 1992). The fire processes simulated includes the spread of fire to neighbouring pixels, as well as the smouldering of a burned pixel. Geometrically, fire growth is based on a deterministic cellular automation process, at 1 ha resolution. The information that drives this process includes the spatial patterns of pixel-based fuel type and topography, as well as daily fire weather indices, wind speed, and wind direction. Different rates of spread are estimated directionally (forward, backward, and flanks) based on the FBP system (Forestry Canada Fire Danger Group 1992), using an elliptical fire growth algorithm (Catchpole et al. 1982).

As soon as a pixel (source pixel) is ignited, BFOLDS's fire spread algorithm uses a 9 x 9 search window around the ignited pixel and directionally varying rate of spread to determine the potential spread to neighbouring pixels. Each of the 32 (target) pixels within the search window (pixels to which an arrow points) is examined for the potential of the fire to spread to it (Figure 8). This involves determining if the target pixel can be burned (that is, if its fuel type is burnable and it is not currently too wet), or if it has already burned or the spread path to it is

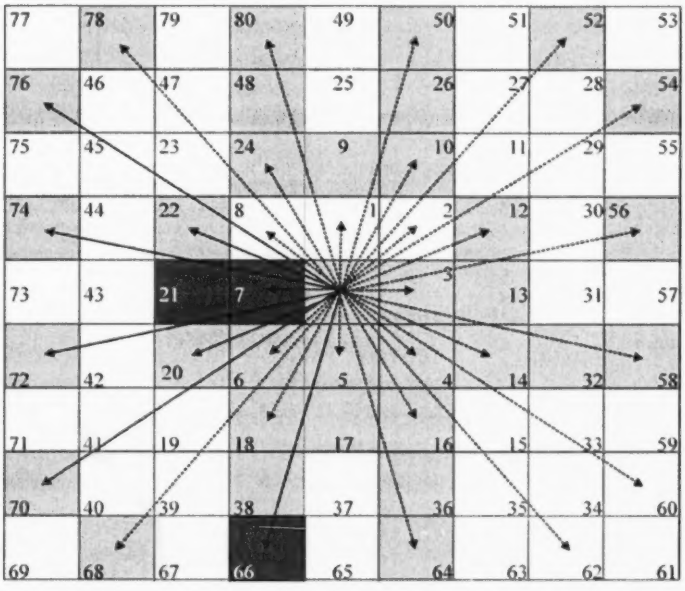

Figure 8. *An illustration of potential fire spread directions from a source pixel (origin of arrows) to target pixels (end of arrows) within a 9 x 9 window that has two flammable fuel types, A (in light gray) and B (in white), and one nonflammable fuel type C (in dark gray). Dotted arrows indicate possible fire spread directions, while black arrows indicate non-spread (due to nonflammable fuel at end pixel, e.g., 7 and 66 or along spread path, e.g. 7 and 21).*

blocked by other non-burnable pixels. For example, target pixels 7, 20, 22, 70, 72, 74, and 76 cannot be burned because nonflammable pixels occur in the path (pixels 7 and/or 21) from the source pixel to them (Figure 8); target pixel 66 cannot be burned because the fuel type in it is not burnable.

For each burnable target pixel c_i, the future time t_i at which the fire will reach that pixel is estimated based on the fire's rate of spread (ROS) at each pixel, including the source pixel, the target pixel, and any pixels in between. These ROS values are determined specifically for each pixel, based on the prevailing weather conditions, topography, and the FBP fuel types in each relevant pixel. For example, for fire to spread from the source pixel to the target pixel 12, it crosses four pixels: the source pixel, pixel 3, pixel 2, and target pixel 12 in sequence.

The time for the fire to travel from the source pixel to the target pixel 12 is calculated as follows (and shown in Figure 9):

$$t_{12} = \left[d_s / ROS_A\right] + \left[d_3 / ROS_A\right] + \left[d_2 / ROS_B\right] + \left[d_{12} / ROS_A\right]$$

where d_s, d_2, d_3, and d_{12} are fire travel distances within source pixel, pixel 2, pixel 3, and target pixel 12, respectively, and ROS_A and ROS_B are fire rates of spread in FBP fuel type A and B, respectively.

When future time t_{12} is reached in the simulation, the pixel will be "burned" if it hasn't burned already (i.e., by fire spread from other burning pixels or directly by an ignition). Then this burned target pixel becomes a new source pixel (centre of a new 9 x 9 search window), and the process described above is applied to it.

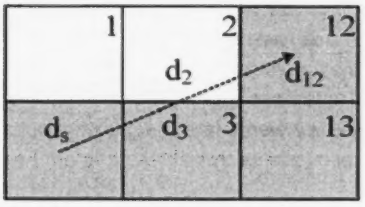

Figure 9. *Illustration of how fire travel distances are calculated, in this case from the source pixel to target pixel 12.*

A just-ignited or just-burned pixel might not immediately spread fire to its neighbours. If the current fire rate of spread is below a threshold, then the cell enters a smouldering state. At periodic future intervals (every three hours as a model assumption), smoldering pixels are re-examined to determine if weather conditions have changed enough for the fire to either spread from it to its neighbours, or be extinguished (see below).

Note that the above fire propagation algorithm will grow or smoulder fires indefinitely unless all growth at the fire perimeter is blocked by permanently and/or currently non-burnable cells, or the fire season ends.

Fire extinguishment

This process represents the extinguishment of fires that are spreading or smouldering. It is also a mechanistic process that is driven by spatio-temporal patterns in weather in the simulated landscape. During a fire season, all pixels that are either burning or smouldering are extinguished when the weather is too wet to sustain a fire. As for ignition and propagation, this process is governed by the DMC value (described in *weather* section).

Specifically, extinguishment occurs when the DMC value drops below a certain threshold, and that threshold value is drawn from a uniform probability distribution of DMC with a mean and a range specified by the user. The default DMC mean is set for 20 (from McAlpine, OMNR, unpublished manuscript) and the range is ±10%. This procedure introduces a stochastic element to fire extinguishment and thus fire regime simulations. Extinguishment process operates on individual pixels, so it is possible that an entire segment of a large fire becomes extinguished if that fire spans the transition where DMC crosses the threshold value. Regardless of DMC, all burning and smouldering fires are extinguished at the end of a simulated fire season.

A discrete-event simulation algorithm is used to advance time and schedule the fire processes that permit multiple fires to ignite, spread, and extinguish simultaneously in a simulated landscape. The major decision steps associated with simulating fire processes daily are illustrated in Figure 10.

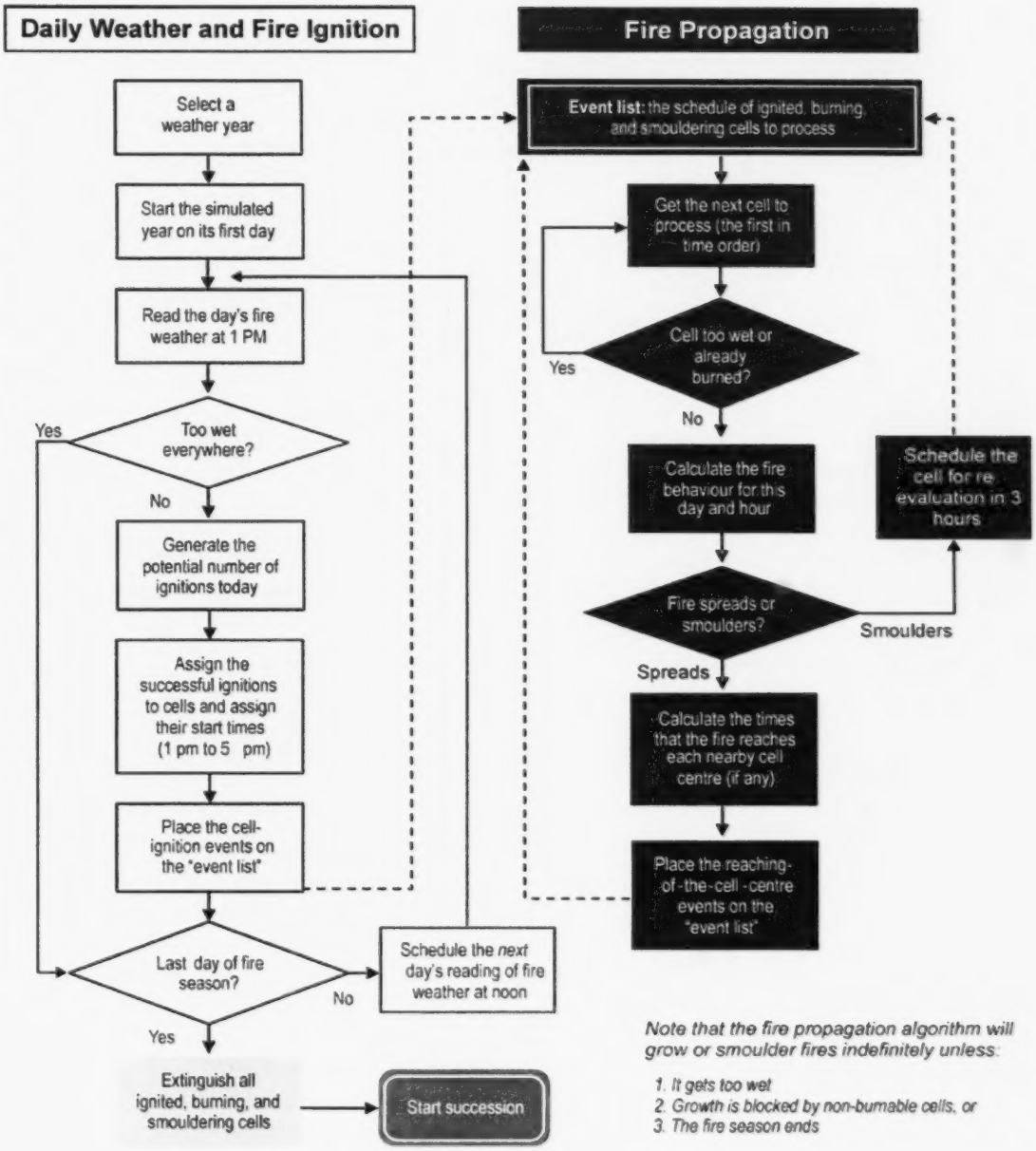
Daily Weather and Fire Ignition
Fire Propagation
Select a weather year
Start the simulated year on its first day
Read the day's fire weather at 1 PM
Too wet everywhere?
Yes
No
Generate the potential number of ignitions today
Assign the successful ignitions to cells and assign their start times (1 pm to 5 pm)
Place the cell-ignition events on the "event list"
Last day of fire season?
No
Yes
Schedule the next day's reading of fire weather at noon
Extinguish all ignited, burning, and smouldering cells
Start succession
Event list: the schedule of ignited, burning, and smouldering cells to process
Get the next cell to process (the first in time order)
Cell too wet or already burned?
Yes
No
Calculate the fire behaviour for this day and hour
Fire spreads or smoulders?
Smoulders
Spreads
Schedule the cell for re-evaluation in 3 hours
Calculate the times that the fire reaches each nearby cell centre (if any)
Place the reaching-of-the-cell-centre events on the "event list"
Note that the fire propagation algorithm will grow or smoulder fires indefinitely unless:
1. It gets too wet
2. Growth is blocked by non-burnable cells, or
3. The fire season ends

Figure 10. *Major decision steps in BFOLDS's fire simulation algorithm.*

Premise and assumptions

BFOLDS simulation of fire processes must be considered in the context of its premise (scale and details of simulation), model assumptions (assumptions made by model authors), and user assumptions (input data, as well as optional assumptions made by model users).

(a) Model premise

A simulated landscape consists of 1 ha square raster cells, and the information provided for fire simulation processes (fuel, weather, terrain) within a pixel are considered spatially and categorically uniform (sub-pixel variability is not considered). Temporally, most weather indices for a given pixel change daily (some hourly) during simulations. All modelled processes are what would happen in the absolute absence of human influence: only lightning-caused fires are modelled, no artificial fire suppression and/or fuel modifications are considered.

(b) Model assumptions

- Fires can only occur and spread within the time window of a fire season, based on start and end dates defined by users. No fires smoulder beyond a fire season.
- Number of successful ignitions for a day is a filtered Poisson process; daily ignition data input by users represents the mean of that probability distribution.
- Locations of successful ignitions are spatially random within a simulated landscape (excluding nonflammable cover types such as water). (This can be modified – see user assumptions below.)
- Once a pixel is burned, all fuel is consumed, and the forest cover is destroyed. (This can be modified – see user assumptions below.)
- A burned pixel cannot reburn within 10 years and acts as a fire break.
- Possible fire ignition is between 1:00 and 5:00 PM, at random times.
- During a fire season, fire processes (ignition and spread) occur only while DMC is higher than the specified threshold value.

(c) User assumptions

- Users may apply their own conversion factors to convert forest cover types to FBP fuel types based on the data.
- Users may assume a non-random sequence for fire weather input as a correlated sequence of fire seasons (for example, to generate a progressive warming trend).
- Assignment of the dates when a fire season begins and ends, as well as when the summer begins and ends, is a user assumption, based on local knowledge of weather patterns.
- Spatial distribution of potential fire ignitions (successful lightning strikes) may be assumed to be non-random (i.e., with spatial biases within a simulated landscape), with a pre-defined biasing pattern.
- The DMC threshold (and the range) at which fires ignite and spread is set at 20 (±10%), but users may change this threshold (as well as the range) based on their experience and local knowledge.
- Users may assume a fire intensity threshold below which a pixel may be declared unburned. This threshold may be set generally, across all cover types, or as a cover type- and/or site type-specific value.

How does BFOLDS simulate forest succession?

Background

Forest fires are the primary natural agent that drives forest succession in boreal forests. Even though occasionally boreal fires may damage only the forest understory, most are intense enough to destroy the existing forest cover (Frelich 2002). Consequently, the spatio-temporal patterns in fire incidences cause boreal forest cover to be a spatially and temporally shifting mosaic that may be most evident at large spatial extents and time periods, given the scale of fire disturbance regime. In turn, this forest cover mosaic determines the spatio-temporal distribution of fuel availability, thereby affecting the probabilities of forest fire incidence across a landscape. Human activities, such as forest harvest and vegetation and/or stand management practices, directly influence forest succession patterns in space and time, in addition to indirect effects of forest fire suppression and prescribed fires.

Once again, in keeping with its goal to allow the exploration of the natural range of possibilities of boreal fire regime, BFOLDS simulates only natural forest succession, which includes forest cover changes that occur through time (aging in the absence of fire) and destruction of forest cover by fire. Because other natural disturbances (for example, windthrow, insect epidemics) are not simulated in BFOLDS, effects of these disturbances on forest succession are not addressed. However, influence of site conditions such as soil moisture and nutrient regime on forest succession is simulated as spatially explicit modifiers of the effects of aging and fire disturbances. Overall, BFOLDS stochastically simulates forest succession in discrete steps of 1 year intervals, based on the spatially explicit information of forest cover composition, its age, soil moisture regime, soil nutrient regime, and incidence of forest fire. Below we describe the details of the principles of forest succession simulation in BFOLDS.

Definition of simulation scale, space, and time

Natural forest succession is change in tree species occurrence or abundance in a given spatially defined area. However, it is not confined to a single spatial or temporal scale of reference; natural succession of tree species can be observed at fine spatio-temporal scales (for example, growth of individual seedlings over weeks, across a canopy gap) or at coarse scales (for example, changes in forest cover over decades or centuries across a large landscape). In BFOLDS simulations, the scale of reference for forest succession matches the scale of forest fire regimes. This coarse scale permits efficiency in requirements for and use of information (van Hulst 1992), and applying simpler model logic is likely to produce more accurate results over longer time scales than are more complex models (Burkhart 2003).

In BFOLDS, the spatial extent of forest succession modelled is large landscapes (millions of hectares), which encompass heterogeneous geo-climates, site conditions, forest cover types, and age classes. The resolution of succession simulations is fixed at 1-ha pixels, which represent the aggregated sub-pixel information on environmental conditions, forest cover, and consequently forest cover changes. Spatial dependence among these 1-ha pixels across a landscape is not ignored, and as described later, succession simulations are biased to account for strong spatial autocorrelations.

Temporal resolution of simulated succession processes is 1 year, to reflect the end result of all processes that occur during a growing season. Though successional events can occur annually throughout a given landscape, at the pixel level they can occur at longer intervals. This is because succession in BFOLDS is modelled as a discrete process, at time steps of 20 years (or 10 or 5 years, as defined by user). For example, once the forest cover type changes in a given pixel, it will remain the same for 20 years (unless burned and destroyed by fire), before succeeding again. Also, as mentioned under description of fire simulation processes, newly established forest cover in a burned pixel cannot burn again for a minimum of 10 years.

Definition of forest cover, forest cover age, and site conditions

Every 1-ha pixel in a simulated landscape is occupied by one forest cover type representing a compositional grouping of species that should be broad, yet fine enough to undergo unique succession trajectories (i.e., one forest cover type can succeed only to another defined cover type or itself). While the specific groupings used in succession simulations may vary (as they are input as user assumptions), they must be informative enough to form the nodes in a forest succession network.

Forest cover age attributed to a pixel is the age of the dominant canopy layer at any given time. This is different from the site age, which is the time elapsed since the pixel last burned. Spatially, forest cover is not grouped as 'stands' *a priori*, but may emerge through forest dynamics as spatially juxtaposed pixels of the same forest cover type and similar forest cover age. Consequently, forest stands may be composed of single pixels or of groups of contiguous pixels, and are transient with subsequent fire-succession dynamics.

All steps in forest succession are affected by a hierarchy of environmental factors: geo-climatic factors (Perry 1994, Oliver and Larson 1990) at broad scales and edaphic factors (Schwarz et al. 2003) at finer scales. Geo-climatic factors such as precipitation, temperature, and growing-degree-days show large-scale spatial variation and operate at the level of the region (Perry 1994), which are addressed in BFOLDS as geo-climatic strata of a simulated forest landscape. Edaphic factors such as soil moisture regime and soil nutrient regime show small-scale spatial variation and operate at the level of the site (Pregitzer et al. 1983), thus are modelled at pixel-level.

Since edaphic factors are likely to be spatially auto-correlated, 1-ha pixels are grouped into spatial neighbourhoods. These neighbourhoods, with homogenous levels of auto-correlation of edaphic factors within, are termed spatial biasing regions and are emergent properties of the landscape (Weaver and Perera 2004). As discussed later, these biasing regions exert partial control over natural succession processes. However, the specific environmental factors and site conditions may vary from one boreal forest landscape to another and with the size of simulated landscape. Therefore, in BFOLDS simulations of forest succession, provisions are made for several sets of site conditions that may act as modifiers of succession trajectories.

Definition of forest succession

Conceptually, forest succession occurs due to the continuous replacement of canopy trees of some species by canopy trees of other species (Horn 1981). In simulations, succession is viewed in steps, where the forest cover of a pixel moves to another when the continuous change in tree species reaches a threshold, and consequently is modelled as discrete probabilistic events (Usher 1992). When these transitions occur on a pixel in the absence of forest fires, merely as a function of aging of the canopy cover and differences in species eco-physiological strategies, it is referred to as *natural succession* (e.g., Horn 1981). A series of such transitions in forest cover during natural succession comprise a succession pathway. If the probability of succeeding to a different cover type is zero, a succession pathway may end, and enter a self-replacement stage where that forest cover persists on a pixel indefinitely (through simulation time) until it burns.

When a pixel burns, and the occupant forest cover is destroyed, the transition to a new forest cover type (or the same forest cover type) is referred to as *post-fire establishment* (e.g., Gutsell and Johnson 2007). Conceptually, post-fire establishment covers the period from the destruction of the previous forest cover by wildfire to the end of the stand initiation phase (Oliver and Larson 1990). After destruction of the forest cover by fire, both site age and forest cover age on that pixel are reset to year 1, and advance with each simulation year.

Probabilities associated with natural forest succession

Forest cover types are connected by natural succession in such a way that the forest cover in a pixel can switch to another cover type; therefore, all forest cover types are inter-connected and form a succession network (Figure 11). Two stochastic elements are involved during the realization of this network. First, succession between forest cover types is a probabilistic process, meaning that given two identical pixels (with same cover type, age, geo-

climate, and site conditions) each one may succeed to a different forest cover type due to probability associated with natural succession.

Second, the timing of the transitions may differ regardless whether they succeed to the same cover type, because this succession timing is probabilistic. Therefore, natural succession is often viewed as a time-dependent Markovian process (Usher 1992, Yemshanov and Perera 2002), meaning that it depends on the extant state of a pixel (i.e., forest cover type), and that this relationship changes with the aging of the forest cover (i.e., forest cover age). In BFOLDS, natural succession is simulated as a time-dependent Markovian process, governed by a set of succession rules designed *a priori* for any simulated landscape.

Mathematically, these rules are expressed as probability matrices, m x m, where m is the number of forest cover types in the simulated landscape; the matrix cell values p_{ii} indicate the probability of a pixel in forest cover type i to remain in that forest cover type, while matrix cell values p_{ij} indicate the probability of a pixel in forest cover type i to succeed to a different forest cover type j. These are time-dependent, with probability values in matrix cells changing with time.

Each matrix is specific for a certain forest cover age as defined by the fixed time intervals for succession (Table 8) and matrix cell values can be written as $p_{ij,a+1}$ indicating the probability of a pixel succeeding from forest cover type i to forest cover type j at forest cover age a+1. Moreover, many such forest cover transition probability matrices are needed to account for combinations of geo-climate and site conditions. As a result, the total number of forest cover transition probability matrices is large, but finite. The hypothetical matrices in Table 8 depict the temporal course of succession of the hypothetical succession network shown in Figure 11.

At forest cover age a, the first matrix (Table 8a) is applied, which indicates that no forest cover transitions are possible (all p_{ij}'s are zero) and that all 1-ha pixels of this forest cover age, across all forest cover types, remain in their extant forest cover type. As forest cover age increases to a+1, the second matrix (Table 8b) is applied to guide forest succession simulation. It indicates that all pixels with forest cover types A and B, at age a+1, will succeed to forest cover type D (p_{ad} and p_{bd} are both 1.0). Pixels in forest cover type H succeed to forest cover types E, F, and G with probabilities of 0.2, 0.2, and 0.6, respectively. Because these probabilities sum to 1.0, all pixels in cover type H must succeed. This implies that no cells of forest cover types A, B, and H will be older than a+1 years. Pixels with other forest cover types (D, E, F, I, and J) remain unchanged at time a+1. As forest cover reaches age a+2, the third matrix (Table 8c) is used. It indicates that pixels with cover types D, F, and G, of age a+2, succeed to forest cover types E, G, and I, respectively, with probability 1.0. Pixels in

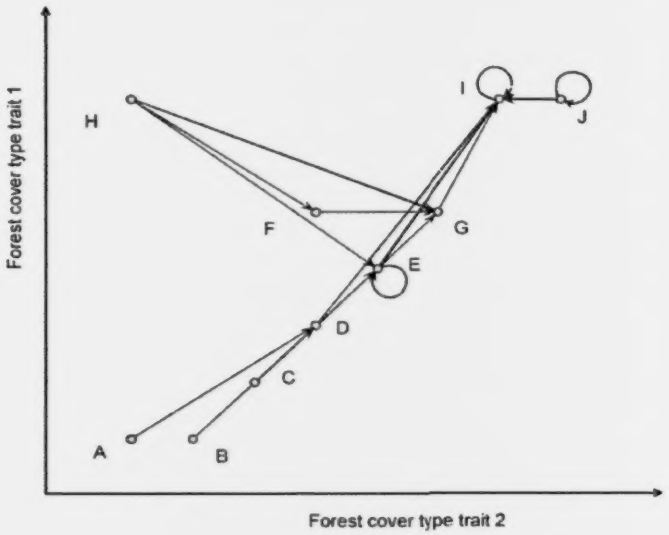

Figure 11. *Illustration of a hypothetical succession network in which forest cover types A – J are inter-connected by natural succession. Arrows indicate direction of succession; a circular arrow indicates self-replacement of a forest cover type. For illustrative purposes, the forest cover types are shown in a space formed by two hypothetical forest cover type traits.*

Table 8. *Hypothetical series of time-dependent, probability matrices formalizing the succession network in Figure 11. Each matrix is specific for a certain forest cover age (a, a+1, … , a+3). Rows indicate the current forest cover type of a pixel; columns indicate the forest cover type to which the forest cover in a pixel can succeed. Non-zero values are shaded for readability.*

(a, forest cover age a)

	A	B	C	D	E	F	G	H	I	J
A	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
B	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
C	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
D	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00
E	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00
F	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00
G	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00
H	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00
I	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00
J	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00

(b, forest cover age a+1)

	A	B	C	D	E	F	G	H	I	J
A	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00
B	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00
C	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
D	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00
E	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00
F	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00
G	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00
H	0.00	0.00	0.00	0.00	0.20	0.20	0.60	0.00	0.00	0.00
I	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00
J	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00

(c, forest cover age a+2)

	A	B	C	D	E	F	G	H	I	J
A	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00
B	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00
C	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00
D	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00
E	0.00	0.00	0.00	0.00	0.80	0.00	0.10	0.00	0.10	0.00
F	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00
G	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00
H	0.00	0.00	0.00	0.00	0.20	0.20	0.60	0.00	0.00	0.00
I	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00
J	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.20	0.80

(d, forest cover age a+3)

	A	B	C	D	E	F	G	H	I	J
A	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00
B	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00
C	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00
D	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00
E	0.00	0.00	0.00	0.00	0.40	0.00	0.10	0.00	0.50	0.00
F	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00
G	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00
H	0.00	0.00	0.00	0.00	0.20	0.20	0.60	0.00	0.00	0.00
I	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00
J	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.50	0.50

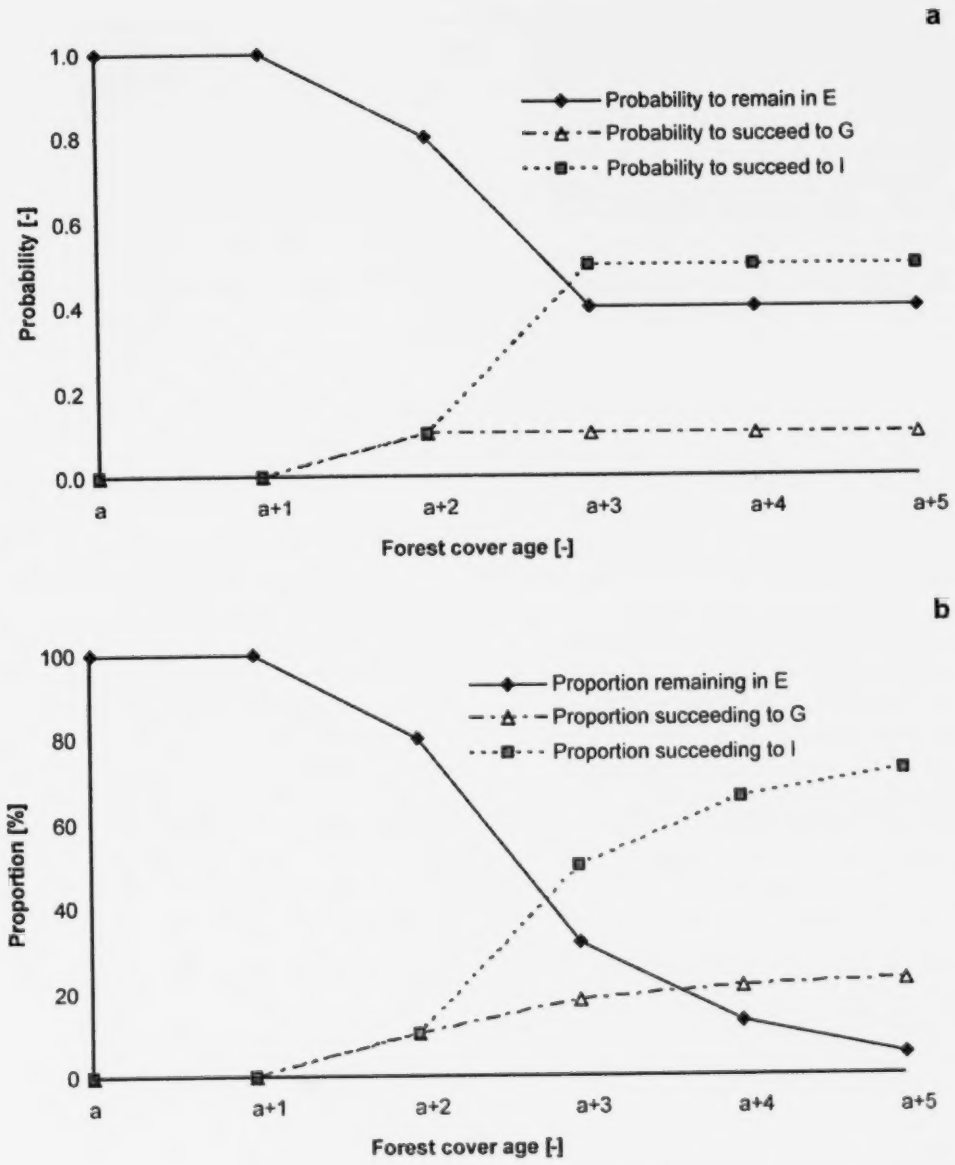

***Figure 12**. Temporal change with forest cover age of (a) probability of cells of forest cover type E to remain in this forest cover type or to succeed to forest cover types G or I, (b) proportion of cells of forest cover type E remaining in this forest cover type or succeeding to forest cover types G or I. Proportional changes are calculated from probability values in Table 8.*

forest cover type E succeed to forest cover types G and I with probability 0.1 each time, and remain unchanged with probability 0.8. Pixels in forest cover type J succeed to forest cover type I with probability 0.2, and remain unchanged with probability 0.8. At forest cover age a+3, the fourth matrix is used (Table 8d) and the shaded cells in the matrix indicate only the probability values of transitions occurred at age a+2 have changed (higher probability of succession from E and J to forest cover types G and I). Pixels with forest cover type I remain unchanged thus far.

If pixel cover age of a cell surpasses the age corresponding to the "oldest" time-dependent matrix (e.g., Table 8d), this "oldest" matrix is used repeatedly (it implies that natural succession processes are not forest cover age dependent beyond this time and it now is a first-order Markovian process). In this example, forest cover type E is partially self-replacing (p_{ee}=0.4) and forest cover type I is completely self-replacing (p_{ii}=1.0). In BFOLDS, the maximum forest cover age for this "oldest" matrix is fixed at 400 years and, consequently, the number of time-dependent matrices used may vary, depending on the assumed time interval, from 19 (20-year interval) to 39 (10-year interval) or 79 (5-year interval).

The above temporal progression of natural succession, as formalized in the probability matrices, can be illustrated by forest cover types as in Figure 12a. Note that the probability matrices indicate *probability* of natural succession and not the *proportion* of pixels in a simulated landscape. However, the proportion of pixels succeeding or remaining unchanged in different forest cover types can be estimated based on the above probabilities, as shown in Figure 12b.

In BFOLDS, the succession step of post-fire establishment of forest cover is not modelled as a function of time but as an instantaneous event following a fire. When a fire destroys the forest cover in a cell, it is replaced by the same or a different forest cover type. A single m x m matrix summarizes these post-fire establishment probabilities, where p_{ii} represent the probability of re-establishing the pre-burn forest cover, and p_{ij} represent the probability of establishing a different forest cover. Again, many such forest cover establishment probability matrices are needed to account for combinations of geo-climate and site conditions. After the establishment stage, the natural succession process described above is simulated until a pixel is burned again.

Simulating natural succession

When a simulation starts in BFOLDS, the forest cover age of each pixel has to be ≥0 years, and subsequently minimum forest cover age at the end of first simulation year is ≥1. Also, the forest cover age in a pixel has to be less than or equal to site age because the dominant canopy trees cannot have survived the previous forest cover-destroying fire. When the forest cover type in a pixel is replaced due to fire, its forest cover age is reset to 1 at the end of the simulation year. When the forest cover in a pixel reaches the maximum forest cover age for this forest cover type, forest cover age is reset to the minimum incoming forest cover age specified *a priori* (Figure 13).

When a pixel succeeds from one forest cover type to another, the forest cover age of the pixel is reset to the incoming forest cover age of the new forest cover type (Figure 14). In BFOLDS, regeneration is simulated as a cohort-level process. When the forest cover in a pixel reaches the age defined by the maximum forest cover type longevity; then (a) the entire canopy tree cohort is replaced by a younger cohort of the same forest cover

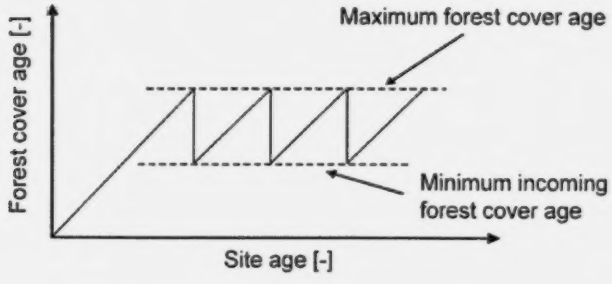

Figure 13. *When the forest cover in a pixel reaches the maximum forest cover age for this forest cover type, age is reset to a user-defined minimum. This process can be repeated until the forest cover type is replaced by another forest cover type or is destroyed by fire.*

type, (b) the forest cover age is set to the age of the younger cohort, and (c) a self-replacement event occurs. If the forest cover in a pixel succeeds from one forest cover type to another, this is also modelled as a cohort replacement event, i.e., the entire canopy tree cohort is replaced by a younger cohort of another forest cover type and the forest cover age is set to the age of the younger cohort.

During a BFOLDS simulation, the natural succession algorithm treats each probability matrix as a set of probability vectors specific to a forest cover type and forest cover age. These summarize the probability of succession from a given forest cover type to all other forest cover types, as shown in the shaded cells of Table 9a. The probability values for natural succession to each forest cover type are used to sub-divide the overall probability interval [0 to 1], where each sub-interval represents the natural succession to a specific forest cover type. These sub-intervals are proportional to the probability of succession to that forest cover type (Table 9b). In the simulation algorithm, self-replacement of a cover type in a pixel or its succession to another forest cover type is decided by drawing random real numbers from the uniform distribution over [0,1] that fall into one of the previously mentioned sub-intervals.

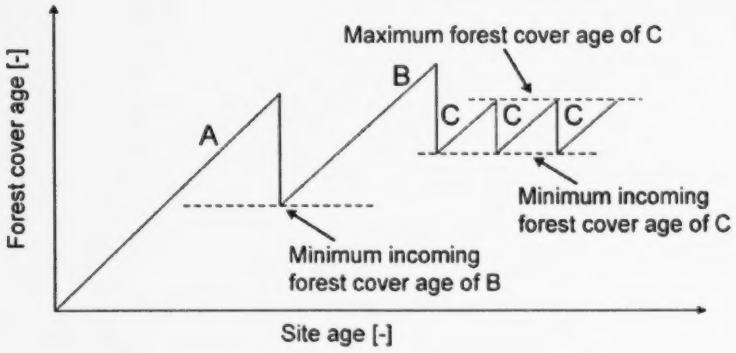

Figure 14. *When a pixel succeeds from forest cover type A to forest cover type B, the forest cover age of the pixel is reset to the user-defined minimum incoming forest cover age of forest cover type B. When the pixel subsequently succeeds to forest cover type C, the forest cover age of the pixel is reset to the minimum incoming forest cover age of forest cover type C. When the pixel subsequently ages without succeeding to another forest cover type, and forest cover age reaches the user-defined maximum forest cover age, it is reset to the minimum incoming forest cover age.*

Table 9. *(a) During a simulation, each probability matrix is interpreted as a set of probability vectors, each one specific for one forest cover type (here the vector for forest cover type H is boxed). (b) The probability values in this vector are used to sub-divide the interval [0,1], where each sub-division corresponds to a forest cover type to which a pixel can succeed. The size of the sub-division is directly proportional to the probability of succession to this forest cover type. The fate of the pixel (self-replacement or succession) is determined by drawing a random real number from the uniform distribution over [0,1] that falls into one of these sub-divisions.*

(a)

	A	B	C	D	E	F	G	H	I	J
A	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00
B	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00
C	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
D	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00
E	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00
F	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00
G	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00
H	0.00	0.00	0.00	0.00	0.20	0.20	0.60	0.00	0.00	0.00
I	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00
J	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00

(b)

	E	F	G
H	[0.00-0.20]	[0.21-0.40]	[0.41-1.00]

Spatial biasing of natural succession

Effects of spatial auto-correlations of edaphic factors on natural succession act as adjustment of the probability vector for pixels in a spatial biasing region (Figure 15).

In this process, a pixel is randomly selected from the landscape (Figure 15a) and undergoes self-replacement (p_{ii}) or succession (p_{ij}) based on the succession simulation process described above. Every other pixel's transition fate (i.e., to self-replace or succeed to another cover type) in the same spatial biasing region depends on its age. If it is eligible to succeed, the probability vector for this second pixel is adjusted by biasing its probability values towards the fate of the first pixel (Figure 15b) by:

$$p^{II}_{ij,Y} = p^{I}_{ij,Y} + x \times (1 - p^{I}_{ij,Y})$$

$$p^{II}_{ij,N} = \frac{p^{I}_{ij,N}}{(1 - p^{I}_{ij,Y})} \times (1 - p^{II}_{ij,Y})$$

Where,

- x is a weighting factor that ranges from 0 to 1, representing the strength of the spatial auto-correlation in the spatial biasing region;
- p_{ij} is the probability of succession from cover type i to j;
- subscript *Y* indicates that the first pixel succeeded to forest cover type j;
- subscript *N* indicates that the first pixel did not succeed to forest cover type j; and
- superscripts I and II indicate the first and second pixel, respectively.

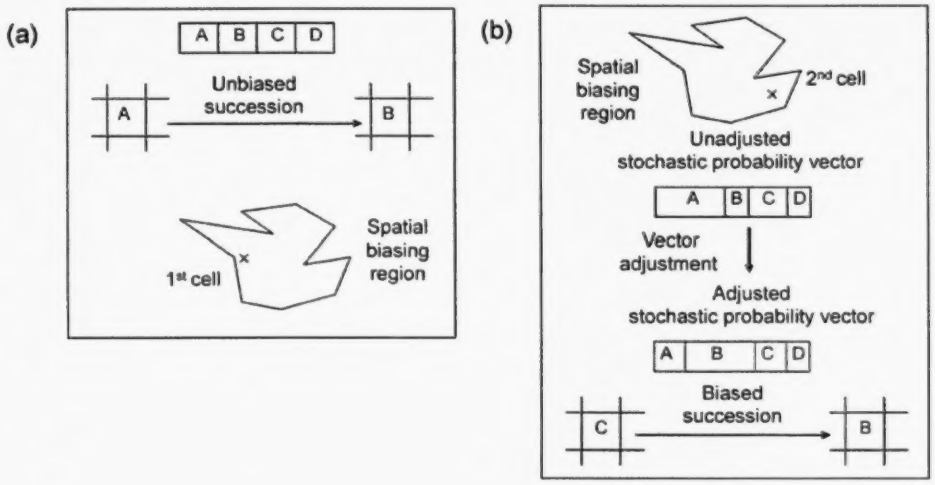

***Figure 15**. Within spatial biasing regions, probability vectors for natural succession are biased to account for the spatially auto-correlated edaphic factors that partially control succession. Spatial biasing is a two-step process: (a) the succession fate (self-replacement or natural succession) of a randomly selected pixel in the biasing region is determined, (b) all pixels from the same biasing region and their probability vectors are adjusted to increase the probability for the same succession fate as has occurred to the first cell; subsequently, this adjusted probability vector is used to determine the succession fate of the second cell.*

However if $p''_{ij,Y}$ is zero, no adjustment is made. Based on this adjusted probability vector, it is subsequently determined whether the second pixel undergoes self-replacement or succession (Figure 15). The net effect of this biasing procedure for the second pixel is that its probability to undergo the same fate as the first pixel is increased, while the probabilities to undergo any other fate are decreased. This procedure is followed for all pixels in the biasing region.

This requires derivation of spatial biasing regions as an input data layer. Since the spatial biasing regions are critical to simulations of natural succession by BFOLDS, here we digress to briefly describe that derivation procedure. For further details, see Weaver and Perera (2004).

The spatial auto-correlation of the main edaphic factors is determined using Moran's I by:

$$I = \frac{\sum_i \sum_j w_{ij} \times c_{ij}}{s^2 \times \sum_i \sum_j w_{ij}}$$

$$c = (z_i - \bar{z}) \times (z_j - \bar{z})$$

$$s^2 = \frac{\sum_i (z_i - \bar{z})^2}{n}$$

Where:

- w_{ij} is a user-defined weighting factor adjusted during spatial data preparation,
- $z_{i,j}$ is the class of edaphic factor z in pixel i or j,
- $\bar{z}$ is the mean value of the edaphic factor over all pixels,
- s^2 is the variance of values of the edaphic factor over all pixels, and
- n is the number of pixels.

Spatial biasing regions are created in several steps, as illustrated in Figure 16, using two edaphic factors. Local auto-correlations for edaphic factor 1 (Figure 16a) and 2 (Figure 16b) are calculated for each pixel in the raster, using non-diagonal pixels (vertical and horizontal only) within a local neighbourhood of 5*5 pixels with the focal pixel at its centre. The Moran's *I* values, which normally range between -1.0 and +1.0 are re-scaled to range from -100 to +100. The two local auto-correlation values for each pixel, one from edaphic factor 1 and one from edaphic factor 2, are combined in a weighted averaging procedure giving different weights to edaphic factor (in this example, 1 for edaphic factor 1 and 4 for edaphic factor 2) autocorrelation values (Figure 16c).

The re-scaled and averaged Moran's *I* values are then grouped into four classes: class 1: $I \leq 0$, class 2: $0 < I \leq 33$, class 3: $33 < I \leq 66$, class 4: $66 < I \leq 100$. All adjacent cells (diagonal, vertical, and horizontal) with identical Moran's *I* class are grouped into spatial regions (Figure 16d). Subsequently, these regions are smoothed by absorbing regions smaller than 25 cells into adjacent larger regions (Figure 15e). Based on the value of the spatial auto-correlation class (1, 2, 3, or 4) within a spatial biasing region, a weighting factor is applied during the adjustment of probability vectors within that spatial biasing region as mentioned above. The value of the weighting factor for auto-correlation classes 2, 3, or 4 is user-defined (to a maximum of 1), but is always zero for class 1 (to indicate zero or negative spatial auto-correlation).

Following a simulated fire event, spatial biasing regions are partially re-shaped as illustrated in Figure 17. The original spatial biasing regions (1, 2, and 3 in Figure 17a) are overlaid with fire scar boundaries (Figure 17b) and new spatial biasing regions (4 and 5 in Figure 17c) are created based on the intersection of regions and fire scars.

These new regions are temporary, lasting only for 60 simulation years, to signal the disappearance of ecological legacy of fire on subsequent succession steps. Biasing regions revert to original state after that time period (Figure 17d). When two fires overlap within the 60 years, the more recent fire erases the spatial biasing regions created by the older fire.

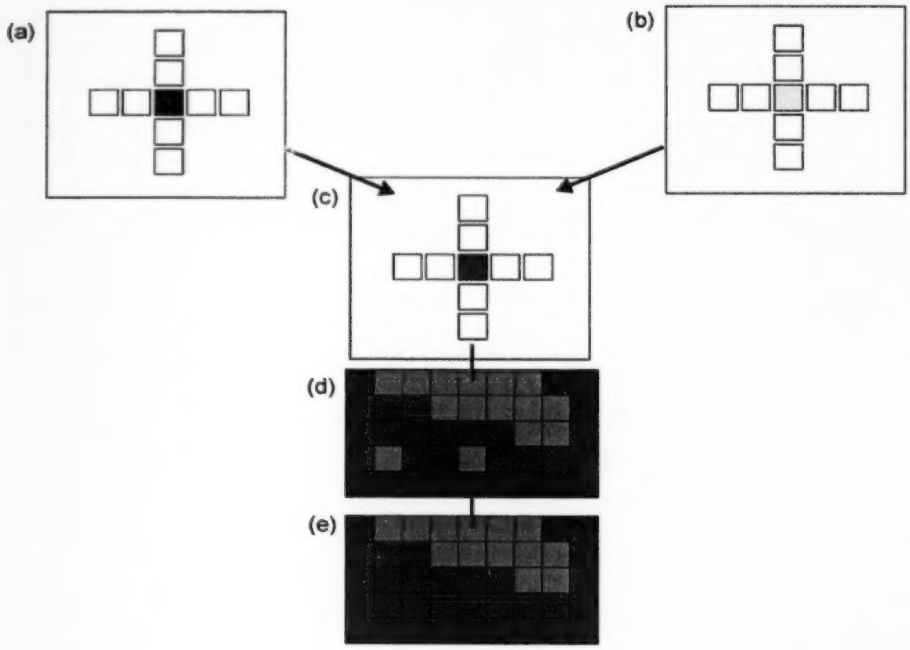

Figure 16. *Spatial biasing regions are created by first determining the local auto-correlations for edaphic factor A (a) and edaphic factor B (b) for each cell in the raster. The two local auto-correlation values for each pixel are combined in a weighted averaging procedure (c). The averaged auto-correlation values are assigned to classes and spatially adjacent cells of the same class are grouped into spatial regions (d). These spatial regions are smoothed by absorbing small regions into adjacent larger regions (e). These smoothed regions are the spatial biasing regions.*

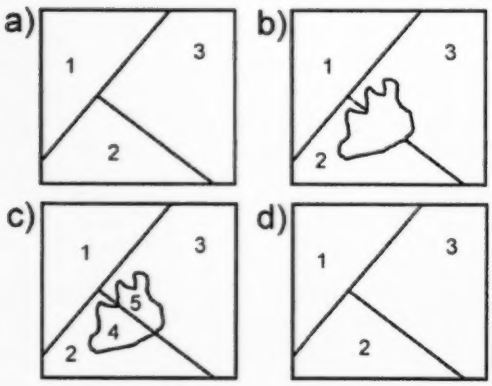

Figure 17. *Wildfires can temporally re-shape the spatial biasing regions: Spatial biasing regions (1, 2, and 3 in a) can be overlaid with fire scar boundaries (b) creating new spatial biasing regions (4 and 5 in c). These new spatial biasing regions can exist for 60 years, after which the biasing regions return to their original state (d).*

Premise and assumptions

BFOLDS simulation of succession processes must be considered in the context of its premise (scale and details of simulation), model assumptions (assumptions made by model authors), and user assumptions (input data as well as optional assumptions made by model users).

(a) Model premise

A simulated landscape consists of 1-ha square pixels, and the information provided for natural forest succession processes (forest cover, cover age, geo-climate, site factors) for each pixel are considered spatially and categorically uniform (sub-pixel variability is not considered). Temporally, all succession processes occur at 1-year intervals during simulations. All modelled processes are what would happen in the absolute absence of human influence: no forest harvest, artificial regeneration, stand manipulations, or prescribed fires are considered.

(b) Model assumptions

- The tree species pool in a simulated area is constant over a simulation period. i.e., there is no immigration of tree species. Extinctions may occur spatially and temporally in the course of succession.
- The only natural disturbance that occurs during the simulation period is forest fire.
- Once a pixel is burned all extant forest cover is destroyed. (This can be modified – see fire simulation user assumptions.)
- Succession processes are simulated at the end of a fire season.
- Spatially explicit effects of forest fires on succession last 60 simulation years.
- Regeneration of burned pixels occurs by cohorts, not by individual trees.

(c) User assumptions

- The simulation period is decided by users (but cannot exceed 400 years).
- User may classify the forest cover types, up to a maximum of 30 classes, in a simulation area.
- All succession rules (probabilities and timing of transitions, self replacement) are user defined.
- Users may assume 5-year, 10-year, or 20-year intervals for succession steps, and construct transition probability matrices accordingly.
- Users may change the spatial biasing weights, which are assigned based on the combination of site factors used to derive biasing regions.

What are appropriate uses of BFOLDS?

A discussion of appropriate use of a simulation model such as BFOLDS may need to be longer and more comprehensive, but here we treat this topic succinctly. The sections below highlight situations where the use of BFOLDS is advantageous, its proper spatio-temporal scope, as well as the necessity of clear and reasonable choice of assumptions. Since we are not able to perceive and address all possible scenarios that users may encounter, and because the ultimate responsibility of wise and proper application of any tool rests with the user, we presume that they will exercise due diligence and prudence in decisions about when and how to apply BFOLDS.

Exploring spatio-temporal variability and probabilities

BFOLDS is intended to be used as an exploratory model, to examine the *potential variability* in characteristics of forest landscape dynamics. As described in the introduction (Figure 1), many outcomes are possible in fire regime and forest succession and some of these events or sequences may not have been observed in the past or present. Simulation modelling with BFOLDS provides an opportunity to explore a range of possibilities based on explicit sets of assumptions (for example, climate, local weather patterns, forest cover composition, and spatial patterns).

Such explorations provide insight to understand the concept referred to as the "natural variability", which has become a basis for managing ecosystems (Landres et al. 1999). Specifically, it is possible to separate this "natural" variability in forest landscape dynamics to three dimensions – spatial, temporal, and random – and examine those individually. Therefore, the most useful aspect of simulation modelling with BFOLDS is the ability to elucidate spatio-temporal and random components of variability in characteristics of fire regime and forest succession, explicitly in relation to what-if assumptions of major causal factors.

Figure 18 illustrates the potential use of BFOLDS to explore fire regime characteristics with a simple example, where fire return interval of a landscape is simulated (an estimate of temporal frequency of fire occurrence). Customarily, the fire return interval is denoted by a single value for a landscape, based on historical evidence of fire occurrence in that area (Figure 18 a). Its interpretation and application are limited because estimates of dimensions of variability, and their association with causal factors, are not feasible. With BFOLDS simulations, fire return interval can be estimated as one value for a landscape with its variance (Figure 18b); as a fire return interval profile – a distribution of many possible fire return interval values, along with their variability (Figure 18c); as a spatially explicit fire return interval map (Figure 18d); or as a map of spatial distribution of fire return intervals, combined with their variability (Figure 18e).

Given its breadth of scale, characteristics of fire regimes and forest succession simulated by BFOLDS are suitable primarily for informing strategic decisions. Examples of such use include development of policies and forest land use plans over large landscapes while considering long time periods. The coarseness in spatial and temporal resolution of information generated by BFOLDS may not be suited for tactical and fine-scale uses such as planning operational forest fire suppression, planning prescribed burns, or predicting forest succession at local site levels. Below is a list of the types of information that can be generated by BFOLDS on large boreal forest landscapes (Table 10). As mentioned earlier, this information can be generated under one set of assumptions or under many assumptions to explore what-if scenarios.

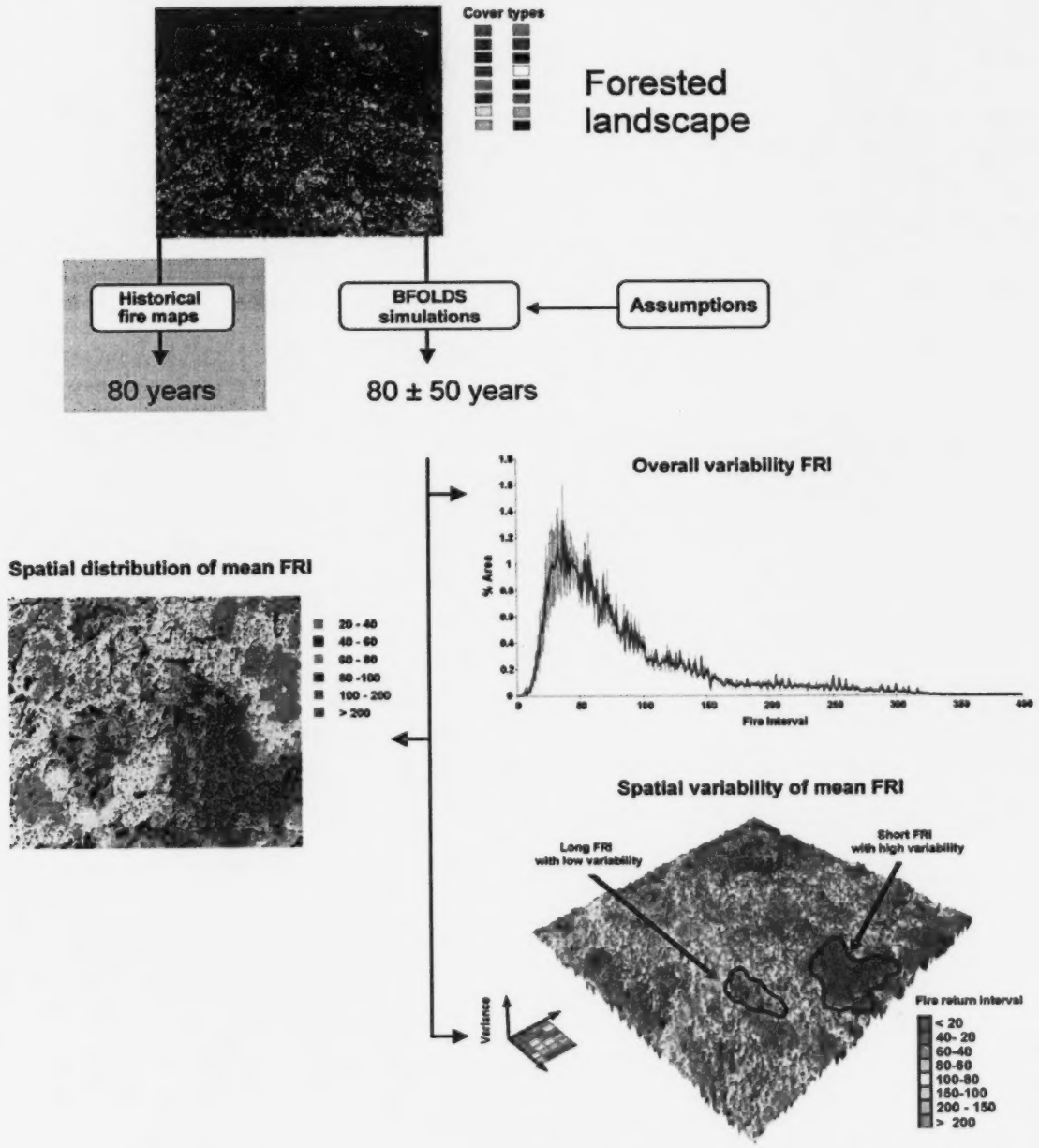

Figure 18. *Estimating fire return interval in a hypothetical forested landscape (a) using historical fire maps and (b-e) using BFOLDS. Given its breadth of scale, characteristics of fire regimes and forest succession simulated by BFOLDS are suitable primarily for informing strategic decisions. Examples of such use include development of policies and forest land use plans over large landscapes while considering long time periods. The coarseness in spatial and temporal resolution of information generated by BFOLDS may not be suited for tactical and fine-scale uses such as planning operational forest fire suppression, planning prescribed burns, or predicting forest succession at local site levels. Below is a list of the types of information that can be generated by BFOLDS on large boreal forest landscapes (Table 10). As mentioned earlier, this information can be generated under one set of assumptions or under many assumptions to explore what-if scenarios.*

Table 10. *Examples of information on forest landscape dynamics that can be generated by BFOLDS for strategic uses such as policy development and land use plans.*

Type of information	Landscape dynamics
Fire disturbance rate	• Mean annual burn rate • Temporal and random variability in annual burn rate • Regional fire return interval
Spatial patterns in fire disturbances	• Spatial probability of burning • Spatial and random variability in fire return interval • Variability in spatial probability of burning • Effect of fire sizes on spatial burn probability
Fire disturbance sizes	• Fire size-class distribution • Temporal and stochastic variability in fire sizes • Spatial probability of fire-size classes
Forest aging patterns	• Site-age and canopy-age class distribution • Variability in age class distribution • Spatial probability of mean and maximum of site age and canopy age • Variability in probability for site age and canopy age
Forest cover patterns	• Temporal forest cover trajectories • Forest cover composition and spatial probabilities • Spatial geometry of forest cover • Spatial, temporal, and stochastic variability in forest cover and spatial geometry

Scale and assumptions

The probabilistic nature of forest landscape dynamics and its variability become readily evident at large extents and long periods. Given its goal of exploring synoptic properties of boreal fire regime and forest succession, BFOLDS is therefore intended to be used at that scale – large forest landscapes and long simulation periods. The largest extent of a landscape simulated with BFOLDS is limited not by model logic or assumptions, but by computing hardware capacity. In our experience with boreal forests in Ontario, landscapes in the range of 1 – 12 million ha were found to be sufficient extents to understand their fire regime. The maximum length of a simulation is limited by model and user assumptions to 400 years. Within BFOLDS, the finest possible resolution for simulations of forest fire regime and forest succession is set to 1 ha. The temporal resolution of fire simulations occurs in variable-length discrete steps on a continuous scale for mechanistic modelling purposes, but the simulation results are aggregated annually. Therefore, the appropriate temporal interval resolution for analyzing and interpreting fire regime simulation results is 1 year.

Forest succession processes are simulated at multi-year (5-20 year) intervals based on user assumptions, which allows users to explore effects of their assumptions on succession processes. BFOLDS is not recommended for exploring fine-scale processes of forest fires and forest succession that are evident and spatial and temporal scales below the scale of model logic, premises, and assumptions. For example, BFOLDS is not an appropriate tool to examine behaviour and patterns of individual fires, predict or forecast fire danger, explore multi-cohort or undergrowth dynamics of forest cover, or generally any sub 1-ha or sub-annual forest dynamics.

As described earlier, BFOLDS has many assumptions associated with its simulations of fire processes and forest succession. All uses of BFOLDS must fall strictly within these assumptions, because they account for lack of knowledge or inadequacies in input data, or sometimes simplify complexities in modelled processes. Some of these assumptions are built into the model algorithms and cannot be changed from simulation to simulation by the user (Figure 19). Other assumptions can be changed by the user from simulation to simulation. In the broadest sense, input data also fall into the category of user assumptions. All these assumptions and their influence on model simulations are explicit, and their relative effect on fire regime simulations can be explored either singly or in combination.

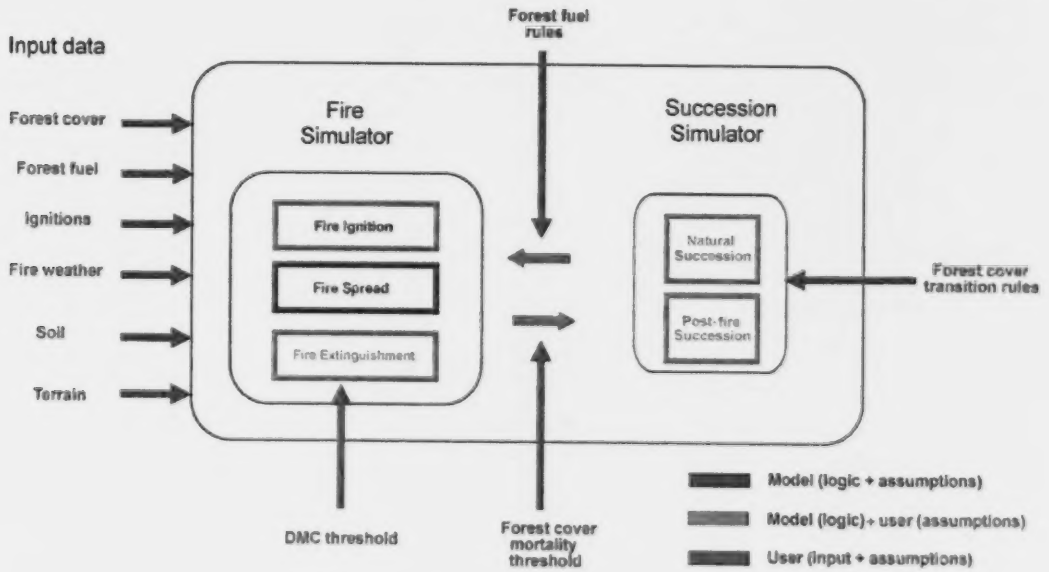

Figure 19. *Schematic depiction of the model assumptions and user assumptions that affect different components of BFOLDS.*

Prior to using BFOLDS, users must understand all model assumptions and the limits those assumptions impose on simulations. For example, BFOLDS assumes that no disturbances, either natural or anthropogenic, other than forest fires would occur during its simulations (we have done so because the scientific knowledge about the probabilities and mechanisms of other disturbances as well as their spatially explicit interactions with fire are not well established). If users cannot agree with this simplification and insist that other disturbances (and their interactions) must be included to understand their landscape, BFOLDS may not be appropriate for their use.

Beyond their input data, which are a set of implicit user assumptions (because data are also abstractions of reality), many opportunities exist for users to explicitly articulate their own assumptions, and thus frame BFOLDS simulations. For example, they can assume rules that govern forest succession; daily, annual, decadal, or even centennial weather patterns under which fires are simulated; or the simulation period, for which all assumptions must be valid. Few model assumptions may be overridden by users with better logic and/or knowledge. While these user assumptions are a powerful tool for exploring their influence on fire regime and forest succession, they also must be used with caution, and careful consideration.

Regardless of the reasons for their inclusion, or grouping, these assumptions provide strict and explicit bounds for simulation exercises, and the context for interpreting and using information generated by BFOLDS, as well as for understanding its limitations in application.

Summary

In this report, we described BFOLDS, boreal forest landscape dynamics simulator, which is a simulation model intended for exploring large scale landscape dynamics over long time periods. The primary focus here was the scientific principles behind the structure and components of the model. The intent was to provide the user with adequate understanding of the underlying model logic and its assumptions, which is a prerequisite to decisions about applying BFOLDS. Informing model user about how to use the software package is the focus of the accompanying user's guide. As well, a case study application of BFOLDS will be detailed in a subsequent document.

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